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Airflow over the *RRS Discovery*: the variation of velocity errors with relative wind direction for anemometers mounted on cruise D223 and D224

B I Moat & M J Yelland

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James Rennell Division for Ocean Circulation and Climate
Southampton Oceanography Centre
University of Southampton
Waterfront Campus
European Way
Southampton
Hants SO14 3ZH
UK

Tel: +44 (0)23 8059 6406
Fax: +44 (0)23 8059 6204
Email: bim@soc.soton.ac.uk

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AUTHOR

MOAT, B I & YELLAND, M J

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ABSTRACT

The Computational Fluid Dynamics (CFD) model VECTIS was used to model the effect of airflow distortion, caused by the hull and superstructure of the ship, on wind speed measurements made during two cruises of the *R.R.S. Discovery.* Wind speed errors are calculated for the positions of the anemometers on cruises D223 and D224. The cruises were instrumented with a total of 9 anemometers for the purpose of evaluating the CFD model.
The VECTIS models considered in this report simulate a boundary layer wind speed profile with a 10 m wind speed of 13.8 ms^{-1}. Wind speed errors were calculated for flows directly over the bow, and for flows at angles of ±15° and ±30° off the bow. This report shows that the errors varied with relative wind direction. The anemometers located on the foremast platform experienced flows which had been both accelerated by up to 5 % and displaced vertically by up to 2m. Anemometers placed above the bridge experienced flows which had been decelerated by up to 15% and displaced vertically by up to 6m.

KEYWORDS

AIRFLOW DISTORTION, COMPUTATIONAL FLUID DYNAMICS, CFD, *DISCOVERY,* WIND SPEED MEASUREMENT, D223, D224

ISSUING ORGANISATION

Southampton Oceanography Centre
University of Southampton
Waterfront Campus
European Way
Southampton SO14 3ZH
UK

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AIRFLOW OVER THE *R.R.S. DISCOVERY*: THE VARIATION OF VELOCITY ERRORS WITH RELATIVE WIND DIRECTION FOR ANEMOMETERS MOUNTED ON CRUISE D223 AND D224

B. I. Moat and M. J. Yelland
July 2001

1. Introduction

The Computational Fluid Dynamics (CFD) package VECTIS was used to model the effect of air flow distortion at anemometer sites on the *R.R.S. Discovery*. Wind speed errors were calculated for the anemometer sites on the VIVALDI '96 cruise D223, which took place from the 28th September to 19th November 1996, and the OMEGA cruise D224. The OMEGA cruise followed VIVALDI and the anemometers remained at virtually the same sites. A fast sampling research sonic anemometer was mounted on the foremast platform and a second was located above the bridge on the mainmast. A Young AQ and a Wind Master sonic were also deployed on the foremast platform to measure instantaneous wind speed and wind direction. In the VIVALDI cruise a six meter *Vector mast* instrumented with five Vector anemometers was located on the foreward edge of the lifeboat deck. The only change in anemometer position between the two cruises was the position of the *Vector mast*. It was moved from the lifeboat deck to the bridge top for the OMEGA cruise.

Three CFD models of a boundary layer flow over the *R.R.S. Discovery* were created; 1) a model with the airflow directly over the bow, 2) 15° off the port bow and 3) 30° off the port bow. The boundary layer profile was logarithmic below 50 m, with a 10 m wind speed of 13.8 ms^{-1}, and almost uniform above 50 m. Effective anemometer positions were created to enable the velocity errors and vertical displacements for winds at 15° and 30° off the starboard bow to be calculated from the two models of the airflow over the port bow (Moat and Yelland, 1997).

This report will document the CFD predicted wind speed errors for the VIVALDI cruise for an airflow at 0° (Section 2), ±15° off the bow (Section 3) and ±30° off the bow (Section 4). With the exception of the *Vector mast* the anemometer positions were the same in both cruises and these results are therefore also applicable to the OMEGA cruise. The wind speed errors for the OMEGA *Vector mast* are presented in Section 5.

2. Wind speed corrections for the *R.R.S. Discovery* VIVALDI cruise at 0° (head to wind)

2.1 Introduction

This section examines the error in the wind speed measurements made from a number of anemometers mounted on *R.R.S. Discovery* cruise D223. The run is at 0° (head to wind) and data are extracted from the VECTIS run 3.1/7. For a full explanation of the convergence characteristics and the wind tunnel geometry, refer to Moat *et al*., (1996).

2.2 Anemometer locations

The regions of the ship where the anemometers are located is indicated in Figure 1. In the VECTIS co-ordinate system (where the origin is at the centre of the ship at sea level), the instrument positions are:

research sonic (starboard side of foremast) x=33.3 m, y=18.58 m, z=2.30 m

Wind Master sonic (port side of foremast) x=33.38 m, y=18.46 m, z=-3.30 m

Young AQ (port side of foremast) x=33.38 m, y=18.36 m, z=-2.30 m

Vector A (lifeboat deck) x=22.22 m, y=15.94 m, z=1.47 m

Vector B (lifeboat deck) x=22.22 m, y=14.94 m, z=1.47 m

Vector C (lifeboat deck) x=22.22 m, y=13.94 m, z=1.47 m

Vector D (lifeboat deck) x=22.22 m, y=12.94 m, z= 1.47 m

Vector E (lifeboat deck) x=22.22 m, y=11.94 m, z=1.47 m

research sonic (starboard side main mast) x=0.9 m, y=25.2 m, z=2.5 m

The foremast anemometers are shown in Figure 2a and the Vector anemometers are shown in Figure 2 b. It is worth noting that the Vector anemometers, in order of height, are Vector A (highest), Vector B, Vector C, Vector D and Vector E (lowest).

2.3 Vertical displacement of the airflow

For a full description of the method used to calculate the vertical displacement of the air and the free stream height, refer to Moat *et al*., (1996).

The vertical K planes may not coincide exactly with the plane of the anemometer.

For the research sonic mounted on the starboard side of the foremast, the local planes are:

K26 z=1.99 m research sonic at z=2.3 m

K27 z=2.99 m

For the research sonic anemometer the airflow has been raised by 1.06 m from its original height before it reaches the anemometer location (Table 1).

location	x (m)	y (m)	z (m)
research sonic	33.30	18.58	2.30
Z_{anemom}	33.33	18.54	1.99
sonic-Z_{anemom}	-0.03	0.039	0.31
Z_{origin}	164.44	17.48	1.99
Z_{anemom}-Z_{origin}	-131.11	**1.06**	0

Table 1 Vertical displacement of the airflow at the research sonic anemometer site.

For the Wind Master sonic mounted on the port side of the foremast, the local planes are:

K20 z=-4.01 m

K21 z=-3.01 m Wind Master sonic at z=-3.3 m

For the Wind Master sonic anemometer the airflow has been raised by 1.09 m from its original height before it reaches the anemometer location (Table 2).

location	x (m)	y (m)	z (m)
Wind Master sonic	33.38	18.46	-3.3
Z_{anemom}	33.31	18.46	-3.01
sonic-Z_{anemom}	0.07	0	-0.29
Z_{origin}	164.49	17.37	-3.01
Z_{anemom}-Z_{origin}	-131.18	**1.09**	0

Table 2 Vertical displacement of the airflow at the Wind Master sonic anemometer site.

For the Young AQ mounted on the port side of the foremast, the local planes are:

K21 z=-3.01 m

K22 z=-2.01 m Young AQ at z=-2.3 m

For the Young AQ anemometer the airflow has been raised by 1.04 m from its original height before it reaches the anemometer location (Table 3).

location	x (m)	y (m)	z (m)
Young AQ	33.38	18.36	-2.3
Z_{anemom}	33.37	18.33	-2.01
Young-Z_{anemom}	0.01	0.03	-0.29
Z_{origin}	189.33	17.29	-2.01
Z_{anemom}-Z_{origin}	-155.96	**1.04**	0

Table 3 Vertical displacement of the airflow at the Young AQ anemometer site.

For the Vector anemometers mounted on the lifeboat deck, the local planes are:

K25 z=0.99 m Vector anemometers at z=1.47 m

K26 z=1.99 m

The displacements of the Vector anemometers are shown in Table 4 and summarised in Table 5.

location	x (m)	y (m)	z (m)
Vector A	22.22	15.94	1.47
Z_{anemom}	22.25	15.95	0.99
Vector -Z_{anemom}	-0.03	-0.01	0.48
Z_{origin}	164.43	14.34	0.99
Z_{anemom}-Z_{origin}	-142.18	**1.61**	0
Vector B	22.22	14.94	1.47
Z_{anemom}	22.26	14.94	0.99
Vector -Z_{anemom}	-0.04	0.00	0.48
Z_{origin}	164.23	13.33	0.99
Z_{anemom}-Z_{origin}	-141.97	**1.61**	0
Vector C	22.22	13.94	1.47
Z_{anemom}	22.20	13.93	0.99
Vector -Z_{anemom}	0.02	0.01	0.48
Z_{origin}	164.32	12.33	0.99
Z_{anemom}-Z_{origin}	-142.12	**1.60**	0
Vector D	22.22	12.94	1.47
Z_{anemom}	22.23	12.97	0.99
Vector -Z_{anemom}	-0.01	-0.03	0.48
Z_{origin}	163.95	11.48	0.99
Z_{anemom}-Z_{origin}	-141.72	**1.49**	0
Vector E	22.22	11.94	1.47
Z_{anemom}	22.25	11.94	0.99
Vector -Z_{anemom}	-0.03	0.00	0.48
Z_{origin}	163.85	10.53	0.99
Z_{anemom}-Z_{origin}	-141.6	**1.41**	0

Table 4 Vertical displacement of the airflow at the Vector anemometer sites.

Vector	A (highest)	B	C	D	E (lowest)
Displacement (m)	1.61	1.61	1.60	1.49	1.41

Table 5 Vertical displacements of the air flow at the Vector anemometer sites, in order of instrument height.

For the research sonic anemometer mounted on the main mast, the local planes are:

K26 z=1.99 m main mast research sonic at z=2.50 m

K27 z=2.99 m

For the main mast research sonic anemometer the airflow has been raised by 2.32 m from its original height before it reaches the anemometer location (Table 6)

location	x (m)	y (m)	z (m)
main mast research sonic	0.90	25.20	2.50
Z_{anemom}	0.94	25.17	1.99
sonic-Z_{anemom}	-0.04	0.03	0.51
Z_{origin}	164.99	22.85	1.99
Z_{anemom}-Z_{origin}	-164.05	**2.32**	0

Table 6 Vertical displacement of the airflow at the main mast research sonic anemometer site.

2.4 Free stream velocities

A value of the wind speed in free stream conditions is required to obtain a wind speed error at the anemometer site. The free stream site used is that towards the edge of the tunnel directly abeam of the anemometer site. The free stream velocity is measured at the height at which the air originated, i.e. the anemometer height minus the amount the air has been raised, (Moat *et al.*, 1996) Free stream velocities, taken from the free stream plane, directly abeam of the anemometer site are shown in Table 7.

Anemometer	Free stream velocity (m/s)	Height free stream velocity originated from (m)
foremast research sonic	14.304	17.48
Wind Master sonic	14.296	17.37
Young AQ	14.294	17.29
Vector A (highest)	14.120	14.34
Vector B	14.052	13.33
Vector C	13.982	12.33
Vector D	13.913	11.48
Vector E (lowest)	13.837	15.53
main mast research sonic	14.59	22.85

Table 7 Free stream velocities for each anemometer.

2.5 Velocities at the anemometer sites

For the method of extracting data refer to Moat *et al.*, (1996)

The percentage wind speed error is given by:

$$\%\ Error = \left(\frac{Average\ Velocity}{Free\ stream\ velocity} - 1 \right) * 100 \qquad (1)$$

Figures 3 to 11 show the lines of velocity data through the research sonic (starboard foremast), Wind Master sonic (port foremast), Young AQ (port foremast), Vector anemometers A to E (life boat deck) and the main mast research sonic (starboard main mast).

The results of all anemometer are summarised in Table 8, which also include the values that the airflow has been displaced.

Anemometer	Velocity from each direction (m/s)	Average velocity at anemometer site (m/s)	Free stream velocity (m/s)	% error	Vertical displacement (m)
research	14.246 (x)				
sonic	14.246 (y)	14.247	14.304	-0.396	1.06
foremast	14.250 (z)				
Wind Master	14.216 (x)				
sonic	14.211 (y)	14.215	14.296	-0.567	1.09
port foremast	14.218 (z)				
Young AQ	14.234 (x)				
port foremast	14.240 (y)	14.238	14.294	-0.392	1.04
	14.240 (z)				
	13.120 (x)				
Vector A	13.078 (y)	13.153	14.120	-6.851	1.61
	13.260 (z)				
	12.878 (x)				
Vector B	12.763 (y)	12.910	14.052	-8.130	1.61
	13.088 (z)				
	11.800 (x)				
Vector C	11.992 (y)	12.021	13.982	-14.023	1.60
	12.272 (z)				
	11.551 (x)				
Vector D	11.540 (y)	11.716	13.913	-15.79	1.49
	12.058 (z)				
	11.621 (x)				
Vector E	11.44 (y)	11.680	13.837	-15.59	1.41
	11.978 (z)				
research	15.133 (x)				
sonic	15.144 (y)	15.138	14.590	3.760	2.32
(main mast)	15.138 (z)				

Table 8 Velocity error estimates for the anemometers at 0° (head to wind).

2.6 Rates of change of velocity at the anemometer sites

This section examines the rate of change of velocity at the anemometer sites using Figures 3 to 11. This gives an indication of the accuracy of the wind speed errors and of the suitability of the location for taking wind speed measurements. The rate of change of velocity is given in terms of change per cell and per meter in Table 9.

Anemometer	Velocity data line	Rate of change of velocity per meter (ms^{-1}/m)	Rate of change of velocity per cell ($ms^{-1}/cell$)
research sonic (starboard foremast)	along (x)	0.002	0.001
	up (y)	0.029	0.029
	across (z)	0.044	0.041
Wind Master sonic port foremast	along (x)	0.002	0.002
	up (y)	0.043	0.012
	across (z)	0.062	0.018
Young AQ port foremast	along (x)	0.004	0.002
	up (y)	0.030	0.011
	across (z)	0.048	0.011
Vector A (highest)	along (x)	0.025	0.029
	up (y)	0.354	0.365
	along (x)	0.257	0.292
Vector B	along (x)	0.05	0.010
	up (y)	0.540	0.537
	across (z)	0.008	0.307
Vector C	along (x)	0.079	0.091
	up (y)	0.613	0.556
	across (z)	0.240	0.140
Vector D	along (x)	0.272	0.259
	up (y)	0.272	0.101
	across (z)	0.188	0.788
Vector E (lowest)	up (y)	0.090	0.165
	across (z)	0.135	0.071
	across (z)	0.636	0.241
research sonic starboard main mast	along (x)	0.025	0.072
	up (y)	0.004	0.005
	across (z)	0.022	0.020

Table 9 Rate of change of velocity for the anemometers at 0° (head to wind).

The rate of change of velocity per meter and per cell is low for both the foremast sonic anemometers and the Young AQ. The Vector anemometers are mounted in an area of high air flow distortion and are intended for validation of the VECTIS code and are not used for wind stress measurement. The research sonic anemometer mounted on the main mast has a very low rate of change of velocity.

2.7 Conclusions

The foremast anemometers are mounted in region of low rates of change of velocity and the wind speed errors range from -0.4 % for the research sonic and Young AQ to -0.6% for the Wind Master sonic. The main mast research sonic anemometer over estimates the wind speed by 3.8% and gives a very low rate of change of velocity in all three direction which suggests the results are reliable and the anemometer is mounted in a well exposed position.

The Vector anemometers mounted above the lifeboat deck are in a region of high airflow disturbance. Across all five Vector anemometers the rate of change of velocity typically reads above 0.2 ms^{-1}/m with rates of change in the vertical of upto 0.6 ms^{-1}/m

3. Wind speed corrections for *R.R.S. Discovery* D223 VIVALDI at ± 15° off the bow

3.1 Introduction

This section examines the error in the wind speed measurements made from a number of anemometers mounted on *R.R.S. Discovery* cruise D223. The run is a surface profile at 15° off the port bow and data are extracted from the VECTIS run 3.1/21 (Moat and Yelland, 1997). Effective anemometer positions have been calculated to simulate a flow over the starboard bow.

3.2 Anemometer locations

The anemometer sites for an airflow 15° over the port bow, in the VECTIS co-ordinate system (where the origin is at the centre of the ship at sea level), are:

research sonic (starboard side of foremast)	x=31.57 m, y=18.58 m, z=10.84 m
Wind Master sonic (port side of foremast	x=33.10 m, y=18.46 m, z=5.45 m
Young AQ (port side of foremast)	x=32.84 m, y=18.36 m, z=6.42 m
Vector A (lifeboat deck)	x=21.08 m, y=15.94 m, z=7.17 m
Vector B (lifeboat deck)	x=21.08 m, y=14.94 m, z=7.17 m
Vector C (lifeboat deck)	x=21.08 m, y=13.94 m, z=7.17 m
Vector D (lifeboat deck)	x=21.08 m, y=12.94 m, z=7.17 m
Vector E (lifeboat deck)	x=21.08 m, y=11.94 m, z=7.17 m
research sonic (starboard side of main mast)	x=0.22 m, y=25.2 m, z=2.65 m

The corresponding anemometer positions for an effective flow over the starboard bow are:

research sonic (starboard side of foremast)	x=32.76 m, y=18.58 m, z=6.40 m
Wind Master sonic (port side of foremast	x=31.39 m, y=18.46 m, z=11.83 m
Young AQ (port side of foremast)	x=31.65 m, y=18.36 m, z=10.86 m
Vector A (lifeboat deck)	x=21.84 m, y=15.94 m, z=4.33 m
Vector B (lifeboat deck)	x=21.84 m, y=14.94 m, z=4.33 m
Vector C (lifeboat deck)	x=21.84 m, y=13.94 m, z=4.33 m
Vector D (lifeboat deck)	x=21.84 m, y=12.94 m, z=4.33 m
Vector E (lifeboat deck)	x=21.84 m, y=11.94 m, z=4.33 m
research sonic (starboard side of main mast)	x=1.52 m, y=25.20 m, z=-2.18 m

The anemometer positions have not changed in relation to the ship, therefore the positions of the foremast anemometers are again indicated in Figure 2a and the Vector anemometer positions are indicated in Figure 2b.

3.3 Vertical displacement of the airflow

3.3.1 Vertical displacement of the airflow for a flow 15° off the port bow

The airflow over the highest Vector anemometer (Vector A) was disturbed by the foremast platform to an extent were it was impossible to measure the vertical displacement of the airflow. All calculations of the velocity error for this anemometer have been left blank.

For the research sonic mounted on the starboard side of the foremast, the local planes are:

K31 z= 10.14 m

K32 z= 11.02 m research sonic at z= 10.84 m

For the research sonic anemometer the airflow has been raised by 1.21 m from its original height before it reaches the anemometer location (Table 10).

location	x (m)	y (m)	z (m)
research sonic	31.57	18.58	10.84
Z_{anemom}	31.60	18.61	11.02
sonic-Z_{anemom}	-0.03	-0.03	-0.18
Z_{origin}	201.50	17.40	11.02
Z_{anemom}-Z_{origin}	-169.90	**1.21**	0

Table 10 Vertical displacement of the airflow at the research sonic anemometer site.

For the Wind Master sonic mounted on the port side of the foremast, the local planes are:

K25 z= 4.53 m

K26 z= 5.75 m Wind Master sonic at z= 5.45 m

For the Wind Master sonic anemometer the airflow has been raised by 1.45 m from its original height before it reaches the anemometer location (Table 11).

location	x (m)	y (m)	z (m)
Wind Master sonic	33.10	18.46	5.45
Z_{anemom}	33.11	18.49	5.75
sonic-Z_{anemom}	-0.01	-0.03	-0.30
Z_{origin}	200.37	17.04	5.75
Z_{anemom}-Z_{origin}	-167.26	**1.45**	0

Table 11 Vertical displacement of the airflow at the Wind Master sonic anemometer site.

For the Young AQ mounted on the port side of the foremast, the local planes are:

K26 z= 5.75 m

K27 z= 6.63 m Young AQ at z= 6.42 m

For the Young AQ anemometer the airflow has been raised by 1.44 m from its original height before it reaches the anemometer location (Table 12).

location	x (m)	y (m)	z (m)
Young AQ	32.84	18.36	6.42
Z_{anemom}	32.89	18.35	6.63
Young-Z_{anemom}	-0.05	0.01	-0.21
Z_{origin}	201.79	16.91	6.63
Z_{anemom}-Z_{origin}	-168.90	**1.44**	0

Table 12 Vertical displacement of the airflow at the Young AQ anemometer site.

For the Vector anemometers mounted on the lifeboat deck, the local planes are:

K27 z= 6.625 m

K28 z= 7.503 m Vector anemometers at z= 7.17 m

The displacements of the Vector anemometers are shown in Table 13 and summarised in Table 14.

location	x (m)	y (m)	z (m)
Vector A	21.08	15.94	7.17
Z_{anemom}	-	-	-
Vector -Z_{anemom}	-	-	-
Z_{origin}	-	-	-
Z_{anemom}-Z_{origin}	-	-	0
Vector B	21.08	14.94	7.17
Z_{anemom}	21.09	14.92	7.50
Vector -Z_{anemom}	-0.01	0.02	-0.33
Z_{origin}	199.25	13.36	7.503
Z_{anemom}-Z_{origin}	-178.16	**1.56**	0
Vector C	21.08	13.94	7.17
Z_{anemom}	21.07	13.96	7.50
Vector -Z_{anemom}	0.01	-0.02	-0.33
Z_{origin}	199.16	12.31	7.50
Z_{anemom}-Z_{origin}	-178.09	**1.65**	0
Vector D	21.08	12.94	7.17
Z_{anemom}	21.09	12.96	7.50
Vector -Z_{anemom}	-0.01	-0.02	-0.33
Z_{origin}	199.03	11.13	7.50
Z_{anemom}-Z_{origin}	-177.94	**1.83**	0
Vector E	21.08	11.94	7.17
Z_{anemom}	21.02	11.91	7.50
Vector -Z_{anemom}	0.06	0.03	-0.33
Z_{origin}	199.03	10.12	7.50
Z_{anemom}-Z_{origin}	-178.01	**1.79**	0

Table 13 Vertical displacement of the airflow at the Vector anemometer sites.

Vector	A (highest)	B	C	D	E (lowest)
Displacement (m)	-	1.56	1.65	1.83	1.79

Table 14 Vertical displacements of the air flow at the Vector anemometer sites, in order of instrument height.

For the research sonic anemometer mounted on the main mast, the local planes are:

K23 z= 1.43 m

K24 z= 2.98 m main mast research sonic at z= 2.65 m

For the main mast research sonic anemometer the airflow has been raised by 2.70 m from its original height before it reaches the anemometer site (Table 15).

location	x (m)	y (m)	z (m)
main mast research sonic	0.22	25.20	2.65
Z_{anemom}	0.23	25.19	2.98
sonic-Z_{anemom}	-0.01	0.01	-0.33
Z_{origin}	200.41	22.49	2.91
Z_{anemom}-Z_{origin}	-200.18	**2.70**	0

Table 15 Vertical displacement of the airflow at the main mast research anemometer site.

3.3.2 Vertical displacement of the airflow for a flow 15° off the starboard bow

For the research sonic mounted on the starboard side of the foremast, the local planes are:

K26 z= 5.75 m

K27 z= 6.63 m research sonic at z= 6.40 m

For the Research sonic anemometer the airflow has been raised by 1.43 m from its original height before it reaches the anemometer location (Table 16).

location	x (m)	y (m)	z (m)
research sonic	32.76	18.58	6.40
Z_{anemom}	32.77	18.61	6.63
sonic-Z_{anemom}	-0.01	-0.03	-0.23
Z_{origin}	201.54	17.18	6.63
Z_{anemom}-Z_{origin}	-168.77	**1.43**	0

Table 16 Vertical displacement of the airflow at the research sonic anemometer site.

For the Wind Master sonic mounted on the port side of the foremast, the local planes are:

K32 z= 11.02 m

K33 z= 11.89 m Wind Master sonic at z= 11.83 m

For the Wind Master sonic anemometer the airflow has been raised by 1.25 m from its original height before it reaches the anemometer location (Table 17).

location	x (m)	y (m)	z (m)
Wind Master sonic	31.39	18.46	11.83
Z_{anemom}	31.41	18.46	11.89
sonic-Z_{anemom}	-0.02	0.00	-0.06
Z_{origin}	202.12	17.21	11.89
Z_{anemom}-Z_{origin}	-170.71	**1.25**	0

Table 17 Vertical displacement of the airflow at the Wind Master sonic anemometer site.

For the Young AQ mounted on the port side of the foremast, the local planes are:

K31 z= 10.14 m

K32 z= 11.02 m Young AQ at z= 10.86 m

For the Young AQ anemometer the airflow has been raised by 1.22 m from its original height before it reaches the anemometer location (Table 12).

location	x (m)	y (m)	z (m)
Young AQ	31.65	18.36	10.86
Z_{anemom}	31.65	18.38	11.02
Young-Z_{anemom}	0.00	-0.02	-0.16
Z_{origin}	201.65	17.16	11.02
Z_{anemom}-Z_{origin}	-170.00	**1.22**	0

Table 18 Vertical displacement of the airflow at the Young AQ anemometer site.

For the Vector anemometers mounted on the lifeboat deck, the local planes are:

K24 z= 2.98 m

K25 z= 4.53 m Vector anemometers at z= 4.33 m

The displacements of the Vector anemometers are shown in Table 19 and summarised in Table 20.

location	x (m)	y (m)	z (m)
Vector A	21.84	15.94	4.33
Z_{anemom}	21.84	15.93	4.53
Vector -Z_{anemom}	0.00	0.01	-0.2
Z_{origin}	202.03	13.40	4.53
Z_{anemom}-Z_{origin}	-180.19	**2.53**	0
Vector B	21.84	14.94	4.33
Z_{anemom}	21.84	14.96	4.53
Vector -Z_{anemom}	0.00	-0.02	-0.2
Z_{origin}	201.85	12.23	4.53
Z_{anemom}-Z_{origin}	-180.00	**2.73**	0
Vector C	21.84	13.94	4.33
Z_{anemom}	21.82	13.95	4.53
Vector -Z_{anemom}	0.02	-0.01	-0.2
Z_{origin}	201.79	11.00	4.53
Z_{anemom}-Z_{origin}	-179.97	**2.95**	0
Vector D	21.84	12.94	4.33
Z_{anemom}	21.84	12.96	4.53
Vector -Z_{anemom}	0.00	-0.02	-0.2
Z_{origin}	201.72	9.78	4.53
Z_{anemom}-Z_{origin}	-179.88	**3.18**	0
Vector E	21.84	11.94	4.33
Z_{anemom}	21.84	11.95	4.53
Vector -Z_{anemom}	0.00	-0.01	-0.2
Z_{origin}	201.63	8.40	4.53
Z_{anemom}-Z_{origin}	-179.79	**3.55**	0

Table 19 Vertical displacement of the airflow at the Vector anemometer sites.

Vector	A (highest)	B	C	D	E (lowest)
Displacement (m)	2.53	2.73	2.95	3.18	3.55

Table 20 Vertical displacements of the air flow at the Vector anemometer sites, in order of instrument height.

For the research sonic anemometer mounted on the main mast, the local planes are:

K20 z= -3.21 m

K21 z= -1.66 m main mast research sonic at z= -2.18 m

For the main mast research sonic anemometer the airflow has been raised by 2.87 m from its original height before it reaches the anemometer location (Table 21).

location	x (m)	y (m)	z (m)
main mast research sonic	1.52	25.20	-2.18
Z_{anemom}	1.54	25.27	-1.66
sonic-Z_{anemom}	-0.02	-0.07	-0.52
Z_{origin}	200.90	22.40	-1.66
Z_{anemom}-Z_{origin}	199.36	**2.87**	0

Table 21 Vertical displacement of the airflow at the main mast research anemometer site.

3.4 Free stream velocities

3.4.1 Free stream velocities for an airflow 15° off the port bow

A value of the wind speed in free stream conditions is required to obtain a wind speed error at the anemometer site. The free stream site used is that towards the edge of the tunnel directly abeam of the anemometer site. The free stream velocity is taken to be from the profile at the height the air originated, i.e. the anemometer height minus the amount the air has been raised (Moat *et al*., 1996). Free stream velocities, taken from the free stream plane, directly abeam of the anemometer sites for the port surface profile and the starboard surface profile are shown in Table 22 and Table 23.

Anemometer (m)	Free stream velocity (m/s)	Height free stream velocity originated from (m)
foremast research sonic	14.330	17.40
Wind Master sonic	14.308	17.04
Young AQ	14.304	16.91
Vector A (highest)	-	-
Vector B	14.082	13.36
Vector C	14.002	12.31
Vector D	13.908	11.13
Vector E (lowest)	13.826	10.12
main mast research sonic	14.593	22.49

Table 22 Free stream velocities at anemometer sites for an airflow 15° off the port bow.

3.4.2 Free stream velocities for an airflow 15° off the starboard bow

Anemometer (m)	Free stream velocity (m/s)	Height free stream velocity originated from (m)
foremast research sonic	14.317	17.18
Wind Master sonic	14.320	17.21
Young AQ	14.316	17.16
Vector A (highest)	14.084	13.40
Vector B	13.998	12.23
Vector C	13.899	11.00
Vector D	13.790	9.78
Vector E (lowest)	13.650	8.4
main mast research sonic	14.587	22.40

Table 23 Free stream velocities at anemometer sites for an airflow 15° off the starboard bow.

3.5 Velocities at anemometer sites

3.5.1 Velocities at anemometers sites for an airflow 15° off the port bow

Figures 12 to 19 show the lines of velocity data through the research sonic (starboard foremast), Wind Master sonic (port foremast), Young AQ (port foremast), Vector anemometers A to E (life boat deck) and the main mast research sonic (starboard main mast). The percentage wind speed error is given by Equation 1.

The results of all anemometer are summarised in Table 24, which also include the values that the airflow has been displaced.

Anemometer	Velocity from each direction (m/s)	Average velocity (m/s)	Free stream velocity (m/s)	% error	Vertical displacement (m)
research sonic (foremast)	14.514 (x)				
	14.516 (y)	14.515	14.330	1.291	1.21
	14.515 (z)				
Wind Master sonic Port foremast	14.303 (x)				
	14.297 (y)	14.301	14.308	-0.0489	1.45
	14.303 (z)				
Young AQ port foremast	14.355 (x)				
	14.346 (y)	14.351	14.304	0.329	1.44
	14.352 (z)				
Vector A	- (x)				
	- (y)	-	-	-	-
	- (z)				
Vector B	13.536 (x)				
	13.494 (y)	13.534	14.082	-3.890	1.56
	13.572 (z)				
Vector C	13.530 (x)				
	13.529 (y)	13.537	14.002	-3.319	1.65
	13.553 (z)				
Vector D	13.448 (x)				
	13.346 (y)	13.420	13.908	-3.566	1.83
	13.467 (z)				
Vector E	12.727 (x)				
	12.942(y)	12.801	13.826	-7.414	1.79
	12.734 (z)				
research sonic (main mast)	15.254 (x)				
	15.260 (y)	15.257	14.593	4.550	2.70
	15.258 (z)				

Table 24 Velocity error estimates at the anemometer sites for an airflow 15° off the port bow.

3.5.2 Velocities at anemometers sites for an airflow 15° off the starboard bow

Figures 20 to 28 show the lines of velocity data through the research sonic (starboard foremast), Wind Master sonic (port foremast), Young AQ (port foremast), Vector anemometers 1 to 5 (life boat deck) and the main mast research sonic (starboard main mast).

The results of all anemometer are summarised in Table 25, which also include the values that the airflow has been displaced.

Anemometer	Velocity from each direction (m/s)	Average velocity (m/s)	Free stream velocity (m/s)	% error	Vertical displacement (m)
research sonic (foremast)	14.362 (x)				
	14.363 (y)	14.363	14.317	0.321	1.43
	14.364 (z)				
Wind Master sonic (port foremast)	14.513 (x)				
	14.508 (y)	14.511	14.320	1.334	1.25
	14.512 (z)				
Young AQ (port foremast)	14.514 (x)				
	14.518 (y)	14.515	14.316	1.392	1.22
	14.514 (z)				
Vector A	13.983 (x)				
	13.954 (y)	13.973	14.084	-0.790	2.53
	13.981 (z)				
Vector B	13.818 (x)				
	13.856 (y)	13.829	13.998	-1.205	2.73
	13.814 (z)				
Vector C	13.714 (x)				
	13.734 (y)	13.720	13.899	-1.285	2.95
	13.713 (z)				
Vector D	13.568 (x)				
	13.522 (y)	13.552	13.790	-1.723	3.18
	13.567 (z)				
Vector E	12.682 (x)				
	12.964(y)	12.769	13.650	-6.452	3.55
	12.662 (z)				
research sonic (main mast)	15.200 (x)				
	15.204 (y)	15.202	14.587	4.214	2.87
	15.201 (z)				

Table 25 Velocity error estimates at the anemometer sites for an airflow 15° off the starboard bow.

3.6 Rates of change of velocity at the anemometer sites

3.6.1 Rates of change of velocity at the anemometer sites for an airflow 15° off the port bow

This section examines the rate of change of velocity around the anemometer site using Figures 12 to 19. This gives an indication of the accuracy of the wind speed errors and of the suitability of the location for taking wind speed measurements. The rate of change of velocity is given in terms of change per cell and per meter in Table 26.

Anemometer	Velocity data line	Rate of change of velocity per meter (ms^{-1}/m)	Rate of change of velocity per cell ($ms^{-1}/cell$)
research sonic (starboard. Foremast)	along (x)	0.027	0.003
	up (y)	0.018	0.008
	across (z)	0.000	0.000
Wind Master sonic (port foremast)	along (x)	0.081	0.017
	up (y)	0.032	0.014
	across (z)	0.015	0.006
Young AQ (port foremast)	along (x)	0.132	0.033
	up (y)	0.026	0.009
	across (z)	0.009	0.001
Vector A	along (x)	-	-
	up (y)	-	-
	across (z)	-	-
Vector B	along (x)	0.033	0.037
	up (y)	0.087	0.044
	across (z)	0.706	0.283
Vector C	along (x)	0.024	0.024
	up (y)	0.045	0.046
	across (z)	0.591	0.055
Vector D	along (x)	0.021	0.021
	up (y)	0.292	0.171
	across (z)	0.477	0.202
Vector E	along (x)	0.043	0.023
	up (y)	0.726	0.670
	across (z)	0.508	0.228
research sonic starboard main mast	along (x)	0.015	0.013
	up (y)	0.012	0.005
	across (z)	0.005	0.001

Table 26 Rates of change of velocity at the anemometer sites for an airflow 15° off the port bow.

The rate of change of velocity per meter and per cell is low for all the sonic anemometers and the Young AQ. The Vector anemometers are mounted in a region of high airflow distortion and are intended for validation of the CFD package and are not used for wind stress calculation.

3.6.2 Rates of change of velocity at the anemometer sites for an airflow 15° off the starboard bow

This section examines the rate of change of velocity around the anemometer site using Figures 20 to 28. This gives an indication of the accuracy of the wind speed errors and of the suitability of the location for taking wind speed measurements. The rate of change of velocity is given in terms of change per cell and per meter in Table 27.

Anemometer	Velocity data line	Rate of change of velocity per meter (ms^{-1}/m)	Rate of change of velocity per cell ($ms^{-1}/cell$)
research sonic (starboard foremast)	along (x)	0.116	0.029
	up (y)	0.019	0.009
	across (z)	0.003	0.003
Wind Master sonic (port foremast)	along (x)	0.028	0.005
	up (y)	0.021	0.008
	across (z)	0.005	0.002
Young AQ (port foremast)	along (x)	0.072	0.003
	up (y)	0.022	0.009
	across (z)	0.075	0.002
Vector A	along (x)	0.0175	0.018
	up (y)	0.096	0.082
	across (z)	0.013	0.004
Vector B	along (x)	0.023	0.022
	up (y)	0.106	0.094
	across (z)	0.001	0.006
Vector C	along (x)	0.028	0.024
	up (y)	0.168	0.128
	across (z)	0.012	0.015
Vector D	along (x)	0.035	0.027
	up (y)	0.383	0.215
	across (z)	0.019	0.015
Vector E	along (x)	0.103	0.077
	up (y)	1.041	1.011
	across (z)	0.21	0.107
research sonic (starboard main mast)	along (x)	0.023	0.015
	up (y)	0.021	0.009
	across (z)	0.013	0.005

Table 27 Rates of change of velocity at the anemometer sites for an airflow 15° off the starboard bow.

The rate of change of velocity per meter and per cell is low for all the sonic anemometers and the Young AQ. The Vector anemometers are mounted in a region of high airflow distortion and are intended for validation of the CFD package and are not used for wind stress calculation.

3.7 Conclusions

For an airflow at ±15° off the bow, the foremast anemometers are mounted in region of low rates of change of velocity. Percentage errors for the port profile simulation range from a 0.05 % underestimate for the Wind Master sonic to an overestimate of 1.3% for the research sonic. Estimates of the velocity errors for the starboard surface profile show a slightly higher distortion at the anemometer sites; an overestimate of 0.3% for the research sonic to an overestimate of 1.4% for the Young AQ anemometer.

The main mast research sonic anemometer over estimates the wind speed by 4.5% (port airflow) and 4.2% (starboard airflow). The anemometer site has low rates of change of velocity for both surface profiles, which suggests the results are reliable and the anemometer is mounted in a well exposed position.

The Vector anemometers mounted above the lifeboat deck are in a region of high airflow disturbance. Across all five Vector anemometers the rate of change of velocity typically reads above 0.1 ms^{-1}/cell.

4. Wind speed corrections for *Discovery* D223 VIVALDI at $\pm 30°$ off the bow

4.1 Introduction

This section examines the error in the wind speed measurements made from a number of anemometers mounted on *R.R.S. Discovery* cruise D223. Data are extracted from the VECTIS run 3.1/19 (Moat and Yelland, 1997). Effective anemometer positions have been calculated to simulate a flow over the starboard bow.

4.2 Anemometer locations

The anemometer sites at 0 degrees to the flow are rotated 30 degrees to starboard and there locations in the VECTIS co-ordinate system(where the origin is at the centre of the ship at sea level) are :

research sonic (starboard side of foremast)	x= 27.69 m, y=18.58 m, z=18.64 m
Wind Master sonic (port side of foremast	x=30.56 m, y=18.46 m, z=13.83 m
Young AQ (port side of foremast)	x=30.06 m, y=18.36 m, z=14.70 m
Vector A (lifeboat deck)	x=18.46 m, y=15.94 m, z=12.47 m
Vector B (lifeboat deck)	x=18.46 m, y=14.94 m, z=12.47 m
Vector C (lifeboat deck)	x=18.46 m, y=13.94 m, z=12.47 m
Vector D (lifeboat deck)	x=18.46 m, y=12.94 m, z=12.47 m
Vector E (lifeboat deck)	x=18.46 m, y=11.94 m, z=12.47 m
research sonic (starboard side main of mast)	x=-0.47 m, y=25.20 m, z=2.61 m

The corresponding anemometer positions for an airflow over the starboard bow are:

research sonic (starboard side of foremast)	x=29.99 m, y=18.58 m, z=14.66 m
Wind Master sonic (port side of foremast	x=27.26 m, y=18.46 m, z=19.55 m
Young AQ (port side of foremast)	x=27.76 m, y=18.36 m, z=18.68 m
Vector A (lifeboat deck)	x=19.98 m, y=15.94 m, z=9.84 m
Vector B (lifeboat deck)	x=19.98 m, y=14.94 m, z=9.84 m
Vector C (lifeboat deck)	x=19.98 m, y=13.94 m, z=9.84 m
Vector D (lifeboat deck)	x=19.98 m, y=12.94 m, z=9.84 m
Vector E (lifeboat deck)	x=19.98 m, y=11.94 m, z=9.84 m
research sonic (starboard side main mast)	x=2.03 m, y=25.20 m, z=-1.72 m

The anemometer positions have not changed in relation to the ship, therefore the positions of the foremast anemometers are again indicated in Figure 1 and the Vector anemometer positions are indicated in Figure 2.

4.3 Vertical displacement of the airflow

4.3.1 Vertical displacement of the airflow for a flow 30° off the port bow

For the research sonic mounted on the starboard side of the foremast, the local planes are:

K37 z= 18.45 m

K38 z= 19.17 m research sonic at 18.64 m

For the research sonic anemometer the airflow has been raised by 1.52 m from its original height before it reaches the anemometer location (Table 28).

location	x (m)	y (m)	z (m)
research sonic	27.69	18.58	16.64
Z_{anemom}	27.69	18.55	18.45
sonic-Z_{anemom}	0.00	0.03	-1.81
Z_{origin}	200.92	17.03	18.45
Z_{anemom}-Z_{origin}	-173.23	**1.52**	0

Table 28 Vertical displacement of the airflow at the research sonic anemometer site.

For the Wind Master sonic mounted on the starboard side of the foremast, the local planes are:

K30 z= 13.08 m

K31 z= 14.14 m Wind Master sonic at 13.83 m

For the Wind Master sonic anemometer the airflow has been raised by 1.79 m from its original height before it reaches the anemometer location (Table 29).

location	x (m)	y (m)	z (m)
Wind Master sonic	30.56	18.46	13.83
Z_{anemom}	30.58	18.44	14.14
sonic-Z_{anemom}	-0.02	0.02	-0.31
Z_{origin}	201.00	16.65	14.135
Z_{anemom}-Z_{origin}	-170.42	**1.79**	0

Table 29 Vertical displacement of the airflow at the Wind Master sonic anemometer site.

For the Young AQ mounted on the starboard side of the foremast, the local planes are:

K31 z= 14.14 m

K32 z= 14.85 m Young AQ at 14.70 m

For the Young AQ anemometer the airflow has been raised by 1.77 m from its original height before it reaches the anemometer location (Table 30).

location	x (m)	y (m)	z (m)
Young AQ	30.06	18.36	14.70
Z_{anemom}	30.06	18.37	14.85
sonic-Z_{anemom}	0.00	-0.01	-0.15
Z_{origin}	200.05	16.60	14.85
Z_{anemom}-Z_{origin}	-169.99	**1.77**	0

Table 30 Vertical displacement of the airflow at the Young AQ anemometer site.

For the Vector anemometers mounted on the lifeboat deck, the local planes are:

K29 z= 11.71 m

K30 z= 13.08 m Vector anemometers at z= 7.17 m

The displacements of the Vector anemometers are shown in Table 31 and summarised in Table 32.

location	x (m)	y (m)	z (m)
Vector A	18.46	15.94	12.47
Z_{anemom}	18.46	15.91	13.08
Vector -Z_{anemom}	0.000	0.03	-0.61
Z_{origin}	201.20	13.00	13.08
Z_{anemom}-Z_{origin}	-182.74	**2.91**	0.000
Vector B	18.46	14.94	12.47
Z_{anemom}	18.46	14.96	13.08
Vector -Z_{anemom}	0.00	-0.02	-0.61
Z_{origin}	201.05	12.10	13.08
Z_{anemom}-Z_{origin}	-182.59	**2.86**	0.000
Vector C	18.46	13.94	12.47
Z_{anemom}	18.42	13.92	13.08
Vector -Z_{anemom}	0.04	0.02	-0.61
Z_{origin}	201.06	10.87	13.08
Z_{anemom}-Z_{origin}	-182.64	**3.05**	0.000
Vector D	18.46	12.94	12.47
Z_{anemom}	18.46	12.98	13.08
Vector -Z_{anemom}	0.0	-0.04	-0.61
Z_{origin}	200.21	9.68	13.08
Z_{anemom}-Z_{origin}	-181.75	**3.30**	0.000
Vector E	18.44	11.94	12.47
Z_{anemom}	18.49	11.94	13.08
Vector -Z_{anemom}	-0.05	0.000	-0.61
Z_{origin}	200.09	8.36	13.08
Z_{anemom}-Z_{origin}	-181.60	**3.58**	0.000

Table 31 Vertical displacement of the airflow at the Vector anemometer sites.

Vector	A (highest)	B	C	D	E (lowest)
Displacement (m)	2.91	2.86	3.05	3.30	3.58

Table 32 Vertical displacements of the air flow at the Vector anemometer sites, in order of instrument height.

For the research sonic mounted on the main mast, the local planes are:

K24 z= 1.88 m research sonic at 2.61 m

K25 z= 4.10 m

For the research sonic anemometer the airflow has been raised by 3.698 m from its original height before it reaches the anemometer location (Table 33).

location	x (m)	y (m)	z (m)
research sonic	-0.47	25.20	2.61
Z_{anemom}	-0.44	25.16	1.88
sonic-Z_{anemom}	-0.03	0.04	0.73
Z_{origin}	243.80	21.47	1.88
Z_{anemom}-Z_{origin}	-244.24	**3.69**	0.00

Table 33 Vertical displacement of the airflow at the main mast research sonic anemometer site.

4.3.2 Vertical displacement of the airflow for a flow 30° off the starboard bow

For the research sonic mounted on the starboard side of the foremast, the local planes are:

K31 z= 14.14 m

K32 z= 14.85 m research sonic at 14.66 m

For the Research sonic anemometer the airflow has been raised by 1.78 m from its original height before it reaches the anemometer location (Table 34).

location	x (m)	y (m)	z (m)
Research sonic	29.99	18.58	14.66
Z_{anemom}	29.96	18.57	14.853
sonic-Z_{anemom}	0.03	-0.01	-0.193
Z_{origin}	200.97	16.79	14.853
Z_{anemom}-Z_{origin}	-171.01	**1.78**	0

Table 34 Vertical displacement of the airflow at the research sonic anemometer site.

For the Wind Master sonic mounted on the starboard side of the foremast, the local planes are:

K38 z= 19.165 m Wind Master sonic at 19.548 m

K39 z= 20.115 m

For the Wind Master sonic anemometer the airflow has been raised by 1.49 m from its original height before it reaches the anemometer location (Table 35).

location	x (m)	y (m)	z (m)
Wind Master sonic	27.26	18.46	19.55
Z_{anemom}	27.27	18.44	19.17
sonic-Z_{anemom}	-0.01	0.02	0.38
Z_{origin}	200.43	16.95	19.17
Z_{anemom}-Z_{origin}	-173.16	**1.49**	0

Table 35 Vertical displacement of the airflow at the Wind Master sonic anemometer site.

For the Young AQ mounted on the starboard side of the foremast, the local planes are:

K37 z= 18.45 m Young AQ at 18.68 m

K38 z= 19.17 m

For the Young AQ anemometer the airflow has been raised by 1.55 m from its original height before it reaches the anemometer location (Table 36).

location	x (m)	y (m)	z (m)
Young AQ	27.76	18.36	18.68
Z_{anemom}	27.72	18.34	18.45
Young-Z_{anemom}	0.04	0.02	0.23
Z_{origin}	199.77	16.79	18.45
Z_{anemom}-Z_{origin}	-172.05	1.55	0

Table 36 Vertical displacement of the airflow at the Young AQ anemometer site.

For the Vector anemometers mounted on the lifeboat deck, the local planes are:

K27 z= 8.533 m

K38 z= 10.337 m Vector anemometers at z= 9.8351 m

The displacements of the Vector anemometers are shown in Table 37 and summarised in Table 38.

location	x (m)	y (m)	z (m)
Vector A	19.98	15.94	9.84
Z_{anemom}	19.98	15.97	10.34
Vector -Z_{anemom}	0.00	-0.03	-0.5
Z_{origin}	199.71	12.63	10.34
Z_{anemom}-Z_{origin}	-179.73	**3.34**	0.000
Vector B	19.98	14.94	9.84
Z_{anemom}	19.91	14.91	10.34
Vector -Z_{anemom}	0.07	0.03	-0.5
Z_{origin}	199.59	11.32	10.34
Z_{anemom}-Z_{origin}	-179.68	**3.59**	0.000
Vector C	19.98	13.94	9.84
Z_{anemom}	19.97	13.99	10.34
Vector -Z_{anemom}	0.01	-0.05	-0.497
Z_{origin}	199.53	10.09	10.337
Z_{anemom}-Z_{origin}	-179.56	**3.90**	0.000
Vector D	19.98	12.94	9.84
Z_{anemom}	19.98	12.96	10.34
Vector -Z_{anemom}	0.001	-0.02	-0.5
Z_{origin}	199.36	8.66	10.34
Z_{anemom}-Z_{origin}	-179.38	**4.30**	0.000
Vector E	19.98	11.94	9.84
Z_{anemom}	19.98	11.98	10.34
Vector -Z_{anemom}	0.00	-0.04	-0.5
Z_{origin}	199.31	7.15	10.34
Z_{anemom}-Z_{origin}	-179.33	**4.83**	0.000

Table 37 Vertical displacement of the airflow at the Vector anemometer sites.

Vector	A (highest)	B	C	D	E (lowest)
Displacement (m)	3.34	3.59	3.90	4.30	4.83

Table 38 Vertical displacements of the air flow at the Vector anemometer sites, in order of instrument height.

For the research sonic mounted on the main mast, the local planes are:

K22 z= -2.56 m research sonic at -1.72 m

K23 z= -0.34 m

For the research sonic anemometer the airflow has been raised by 3.58 m from its original height before it reaches the anemometer location (Table 39).

location	x (m)	y (m)	z (m)
research sonic	2.03	25.20	-1.72
Z_{anemom}	2.06	25.18	-2.56
sonic-Z_{anemom}	-0.03	0.02	0.84
Z_{origin}	200.65	21.60	-2.560
Z_{anemom}-Z_{origin}	-198.59	**3.58**	0.000

Table 39 Vertical displacement of the airflow at the main mast research sonic anemometer site.

4.4 Free stream velocities at anemometer sites

4.4.1 Free stream velocities for an airflow 30° off the port bow

A value of the wind speed in free stream conditions is required to obtain a wind speed error at the anemometer site. The free stream site used is that towards the edge of the tunnel directly abeam of the anemometer site. The free stream velocity is taken to be from the profile at the height the air originated, i.e. the anemometer height minus the amount the air has been raised (Moat *et al.*, 1996). Free stream velocities, taken from the free stream plane, directly abeam of the anemometer sites for the port and starboard surface profiles are shown in Table 40 and Table 41.

Anemometer (m)	Free stream velocity (m/s)	Height free stream velocity originated from (m)
foremast research sonic	14.298	17.03
Wind Master sonic	14.276	16.65
Young AQ	14.272	16.60
Vector A (highest)	14.044	13.00
Vector B	13.978	12.10
Vector C	13.880	10.87
Vector D	13.769	9.68
Vector E (lowest)	13.639	8.36
main mast research sonic	14.529	21.47

Table 40 Free stream velocities at anemometer sites for an airflow 30° off the port bow

4.4.2 Free stream velocities for an airflow 30° off the starboard bow

Anemometer (m)	Free stream velocity (m/s)	Height free stream velocity originated from (m)
foremast research sonic	14.283	16.79
Wind Master sonic	14.294	16.95
Young AQ	14.284	16.79
Vector A (highest)	14.014	12.63
Vector B	13.918	11.32
Vector C	13.086	10.09
Vector D	13.672	8.66
Vector E (lowest)	13.492	7.15
main mast research sonic	14.534	21.60

Table 41 Free stream velocities at anemometer sites for an airflow 30° off the starboard bow.

4.5 Velocities at anemometer sites

4.5.1 Velocities at anemometers sites for an airflow 30° off the port bow

Figures 29 to 37 show the lines of velocity data through the research sonic (starboard foremast), Wind Master sonic (port foremast), Young AQ (port foremast), Vector anemometers 1 to 5 (life boat deck) and the main mast research sonic (starboard main mast). The percentage wind speed error is given by Equation 1.

The results of all anemometer are summarised in Table 42, which also include the values that the airflow has been displaced.

Anemometer	Velocity from each direction (m/s)	Average velocity (m/s)	Free stream velocity (m/s)	% error	Vertical displacement (m)
research sonic (foremast)	14.884 (x)				
	14.879 (y)	14.881	14.298	4.078	1.52
	14.880 (z)				
Wind Master sonic (port foremast)	14.489 (x)				
	14.489 (y)	14.488	14.276	1.485	1.79
	14.486 (z)				
Young AQ (port foremast)	14.580 (x)				
	14.581 (y)	14.579	14.272	2.153	1.77
	14.577 (z)				
Vector A	14.695 (x)				
	14.699 (y)	14.686	14.044	4.574	2.91
	14.665 (z)				
Vector B	14.680 (x)				
	14.687 (y)	14.677	13.978	5.003	2.86
	14.665 (z)				
Vector C	14.657 (x)				
	14.664 (y)	5.574	13.880	5.574	3.05
	14.640 (z)				
Vector D	14.603 (x)				
	14.606 (y)	14.600	13.769	6.038	3.30
	14.592 (z)				
Vector E	14.459 (x)				
	14.428(y)	14.446	13.639	5.919	3.58
	14.452 (z)				
research sonic (main mast)	15.414 (x)				
	15.404 (y)	15.411	14.529	6.073	3.69
	15.416 (z)				

Table 42 Velocity error estimates at the anemometer sites with a surface profile 30 degrees off the port bow.

4.5.2 Velocities at anemometers sites for an airflow 30° off the starboard bow

Figures 38 to 46 show the lines of velocity data through the research sonic (starboard foremast), Wind Master sonic (port foremast), Young AQ (port foremast), Vector anemometers A to E (life boat deck) and the main mast research sonic (starboard main mast).

The results of all anemometer are summarised in Table 43, which also include the values that the airflow has been displaced.

Anemometer	Velocity from each direction (m/s)	Average velocity (m/s)	Free stream velocity (m/s)	% error	Vertical displacement (m)
research sonic (foremast)	14.576 (x)				
	14.577 (y)	14.578	14.283	2.063	1.79
	14.580 (z)				
Wind Master sonic (port foremast)	14.900 (x)				
	14.902 (y)	14.898	14.294	4.226	1.49
	14.892 (z)				
Young AQ (port foremast)	14.886 (x)				
	14.888 (y)	14.886	14.284	4.215	1.55
	14.884 (z)				
Vector A	14.466 (x)				
	14.484 (y)	14.461	14.014	3.192	3.34
	14.434 (z)				
Vector B	14.398 (x)				
	14.432 (y)	14.407	13.918	3.513	3.59
	14.391 (z)				
Vector C	14.349 (x)				
	14.372 (y)	14.354	13.086	9.692	3.90
	14.342 (z)				
Vector D	14.288 (x)				
	14.298 (y)	14.289	13.672	4.518	4.30
	14.283 (z)				
Vector E	14.219 (x)				
	14.203 (y)	14.214	13.492	5.349	4.83
	14.219 (z)				
research sonic (main mast)	15.242 (x)				
	15.236 (y)	15.243	14.534	4.881	3.58
	15.252 (z)				

Table 43 Velocity error estimates at the anemometer sites with a surface profile 30° off the starboard bow.

4.6 Rates of change of velocity at the anemometer sites

4.6.1 Rates of change of velocity at the anemometer sites for an airflow 30° off the port bow

This section examines the rate of change of velocity around the anemometer site using Figures 29 to 37. This gives an indication of the accuracy of the wind speed errors and of the suitability of the location for taking wind speed measurements. The rate of change of velocity is given in terms of change per cell and per meter in Table 44.

Anemometer	Velocity data line	Rate of change of velocity per meter (ms^{-1}/m)	Rate of change of velocity per cell ($ms^{-1}/cell$)
research sonic (starboard foremast)	along (x)	0.031	0.009
	up (y)	0.027	0.011
	across (z)	0.093	0.009
Wind Master sonic (port foremast)	along (x)	0.051	0.010
	up (y)	0.0275	0.003
	across (z)	0.055	0.029
Young AQ (port foremast)	along (x)	0.073	0.018
	up (y)	0.014	0.004
	across (z)	0.034	0.008
Vector A	along (x)	0.034	0.070
	up (y)	0.016	0.018
	across (z)	0.044	0.040
Vector B	along (x)	0.055	0.058
	up (y)	0.018	0.020
	across (z)	0.051	0.031
Vector C	along (x)	0.069	0.072
	up (y)	0.040	0.041
	across (z)	0.051	0.036
Vector D	along (x)	0.094	0.097
	up (y)	0.117	0.028
	across (z)	0.037	0.032
Vector E	along (x)	0.120	0.123
	up (y)	0.489	0.281
	across (z)	0.027	0.008
research sonic (main mast)	along (x)	0.003	0.003
	up (y)	0.027	0.038
	across (z)	0.014	0.016

Table 44 Rates of change of velocity at the anemometer sites for an airflow 30° off the port bow.

The rate of change of velocity per meter and per cell is low for all the sonic anemometers and the Young AQ. The Vector anemometers are mounted in a region of high airflow distortion and are intended for validation of the CFD package and are not used for wind stress calculation.

4.6.2 Rates of change of velocity at the anemometer sites for an airflow 30° off the starboard bow

This section examines the rate of change of velocity around the anemometer site using Figures 38 to 46. This gives an indication of the accuracy of the wind speed errors and of the suitability of the location for taking wind speed measurements. The rate of change of velocity is given in terms of change per cell and per meter in Table 45.

Anemometer	Velocity data line	Rate of change of velocity per meter (ms^{-1}/m)	Rate of change of velocity per cell ($ms^{-1}/cell$)
research sonic (starboard foremast)	along (x)	0.071	0.0196
	up (y)	0.003	0.00315
	across (z)	0.0345	0.0103
Wind Master sonic (port foremast)	along (x)	0.009	0.0032
	up (y)	0.001	0.0007
	across (z)	0.028	0.007
Young AQ (port foremast)	along (x)	0.030	0.0087
	up (y)	0.032	0.0113
	across (z)	0.084	0.0082
Vector A	along (x)	0.044	0.2386
	up (y)	0.0495	0.0604
	across (z)	0.0725	0.1698
Vector B	along (x)	0.073	0.0794
	up (y)	0.056	0.0564
	across (z)	0.077	0.0582
Vector C	along (x)	0.096	0.1067
	up (y)	0.065	0.0596
	across (z)	0.077	0.0552
Vector D	along (x)	0.142	0.1596
	up (y)	0.085	0.0759
	across (z)	0.066	0.0432
Vector E	along (x)	0.228	0.261
	up (y)	0.120	0.0783
	across (z)	0.023	0.011
research sonic (main mast)	along (x)	0.095	0.03005
	up (y)	0.018	0.0234
	across (z)	0.0365	0.0414

Table 45 Rates of change of velocity at the anemometer sites for an airflow 30° off the starboard bow.

The rate of change of velocity per meter and per cell is low for all the sonic anemometers and the Young AQ. The Vector anemometers are mounted in a region of high airflow distortion and are intended for validation of the CFD package and are not used for wind stress calculation.

4.7 Conclusions

For an airflow at ±30° off the bow, the foremast anemometers are mounted in region of low rates of change of velocity. Percentage errors for the port profile simulation range from a 1.5 % overestimate for the Wind Master sonic to an overestimate of 4.1 % for the research sonic. Estimates of the velocity errors for the starboard surface profile show higher distortion at the anemometer sites; an overestimate of 2.1 % for the research sonic to an overestimate of 4.2 % for the Wind Master sonic anemometer.

The main mast research sonic anemometer over estimates the wind speed by 6.1% (port surface profile) and 4.9 % (starboard surface profile). The anemometer site has low rates of change of velocity for both surface profiles, which suggests the results are reliable and the anemometer is mounted in a well exposed position.

The Vector anemometers mounted above the lifeboat deck are in a region of high airflow disturbance. Across all five Vector anemometers the rate of change of velocity typically reads above 0.1 ms^{-1}/m.

5. Wind speed corrections for the *R.R.S. Discovery* D224 OMEGA cruise for flows at 0, ± 15° and ±30° off the bow

5.1 Introduction

The meteorological instrumentation for the *R.R.S. Discovery* cruise D224 was similar to D223. The only alteration made was the movement of the *Vector mast* from the life boat deck to the bridge top. The flow distortion to the new Vector anemometer locations is discussed in this section. The results for the previous sections apply to the foremast anemometers.

5.2 Wind speed corrections for R.R.S. Discovery D224 OMEGA at 0°

5.2.1 Anemometer locations

The locations of the anemometers sites, in the VECTIS co-ordinate system (where the origin is at the centre of the ship at sea level), are:

Vector A (bridge top)	x=8.64 m, y=20.15 m, y=0m
Vector B (bridge top)	x=8.64 m, y=19.15 m, y=0 m
Vector C (bridge top)	x=8.64 m, y=18.15 m, y=0 m
Vector D (bridge top)	x=8.64 m, y=17.15 m, y=0 m
Vector E (bridge top)	x=8.64 m, y=16.15 m, y=0 m

The position of the CFD mast is indicated in Figure 1 and Figure 47. It is worth noting that the Vector anemometers, in order of height, are Vector A (highest), Vector B, Vector C, Vector D and Vector E (lowest).

5.2.2 Vertical displacement of the airflow

For a full description of the method used to calculate the vertical displacement of the air and the free stream height, refer to Moat *et al*., (1996).

The vertical (K planes) may not coincide exactly with the plane of the anemometer.

For the Vector anemometers mounted on the monkey island, the local planes are:

K24	z= 0.001 m	Vectors at z= 0.0 m

The displacements of the Vector anemometers are shown in Table 46 and summarised in Table 47.

location	x (m)	y (m)	z (m)
Vector A	8.64	20.15	0
Z_{anemom}	8.66	20.15	0
Vector -Z_{anemom}	-0.02	0.00	0
Z_{origin}	189.02	17.61	0
Z_{anemom}-Z_{origin}	-180.36	**2.54**	0
Vector B	8.64	19.15	0
Z_{anemom}	8.66	19.12	0
Vector -Z_{anemom}	-0.02	0.03	0
Z_{origin}	188.99	16.37	0
Z_{anemom}-Z_{origin}	-180.33	**2.75**	0
Vector C	8.64	18.15	0
Z_{anemom}	8.66	18.15	0
Vector -Z_{anemom}	-0.02	0.00	0
Z_{origin}	188.88	15.38	0
Z_{anemom}-Z_{origin}	-180.22	**2.77**	0
Vector D	8.64	17.15	0
Z_{anemom}	8.65	17.15	0
Vector -Z_{anemom}	-0.01	0.00	0
Z_{origin}	188.81	14.43	0
Z_{anemom}-Z_{origin}	-180.16	**2.72**	0
Vector E	8.64	16.15	0
Z_{anemom}	8.66	16.14	0
Vector -Z_{anemom}	-0.02	0.01	0
Z_{origin}	188.71	13.03	0
Z_{anemom}-Z_{origin}	-180.05	**3.11**	0

Table 46 Vertical displacement of the airflow at the Vector anemometer sites on D224.

Vector	A (highest)	B	C	D	E (lowest)
Displacement (m)	**2.54**	**2.75**	**2.77**	**2.72**	**3.11**

Table 47 Vertical displacements of the air flow at the Vector anemometer sites, in order of instrument height.

5.2.3 Free stream velocities

A value of the wind speed in free stream conditions is required to obtain a wind speed error at the anemometer site. The free stream site used is that towards the edge of the tunnel directly abeam of the anemometer site. The free stream velocity is taken to be from the profile at the height the air originated, i.e. the anemometer height minus the amount the air has been raised (Moat *et al.*, 1996). Free stream velocities, taken from the free stream plane, directly abeam of the anemometer site are shown in Table 48.

Anemometer (m)	Free stream velocity (m/s)	Height free stream velocity originated from (m)
Vector A (highest)	14.328	17.61
Vector B	14.260	16.37
Vector C	14.200	15.38
Vector D	14.140	14.43
Vector E (lowest)	14.046	13.03

Table 48 Free stream velocities for each Vector anemometer on D224.

5.2.4 Velocities at the anemometer sites

Figures 48 to 52 show the lines of velocity data through the Vector anemometers 1 to 5 (bridge top). The percentage wind speed error is given by Equation 1.

The results of all anemometer are summarised in Table 49, which also include the values that the airflow has been displaced.

Anemometer	Velocity from each direction (m/s)	Average velocity (m/s)	Free stream velocity (m/s)	% error	Vertical displacement (m)
Vector A	14.249 (x)				
	14.172 (y)	14.224	14.328	-0.724	2.54
	14.252 (z)				
Vector B	13.778 (x)				
	13.893 (y)	13.790	14.260	-3.294	2.75
	13.700 (z)				
Vector C	13.820 (x)				
	13.503 (y)	13.821	14.200	-2.669	2.77
	13.822 (z)				
Vector D	13.280 (x)				
	13.300 (y)	13.284	14.140	-6.056	2.72
	13.271 (z)				
Vector E	13.088 (x)				
	13.060(y)	13.078	14.046	-6.892	3.11
	13.086 (z)				

Table 49 Velocity error estimates at the Vector anemometer sites on D224 (head to wind).

5.2.5 Rates of change of velocity at the anemometer sites

This section examines the rate of change of velocity around the anemometer site using Figures 48 to 52. This gives an indication of the accuracy of the wind speed errors and of the suitability of the location for taking wind speed measurements. The rate of change of velocity is given in terms of change per cell and per meter in Table 50.

Anemometer	Velocity data line	Rate of change of velocity per meter (ms^{-1}/m)	Rate of change of velocity per cell ($ms^{-1}/cell$)
Vector A	along (x)	0.086	0.203
	up (y)	0.261	0.409
	across (z)	0.015	0.016
Vector B	along (x)	0.081	0.194
	up (y)	0.332	0.445
	across (z)	0.025	0.026
Vector C	along (x)	0.083	0.198
	up (y)	0.295	0.445
	across (z)	0.026	0.027
Vector D	along (x)	0.369	0.190
	up (y)	0.221	0.091
	across (z)	0.002	0.024
Vector E	along (x)	0.671	0.452
	up (y)	0.170	0.048
	across (z)	0.007	0.272

Table 50 Rate of change of velocity close to the Vector anemometer sites on D224.

5.3 Wind speed corrections for Discovery D224 OMEGA at ± 15° off the bow

5.3.1 Anemometer locations

The locations of the anemometers sites, in the VECTIS co-ordinate system (where the origin is at the centre of the ship at sea level), are:

Vector A (bridge top) x=8.35 m, y=20.15 m, z=2.24 m

Vector B (bridge top) x=8.35 m, y=19.15 m, z=2.24 m

Vector C (bridge top) x=8.35 m, y=18.15 m, z=2.24m

Vector D (bridge top) x=8.35 m, y=17.15 m, z=2.24 m

Vector E (bridge top) x=8.35 m, y=16.15 m, z=2.24 m

As the anemometers are located on the center line of the ship no effective starboard flow need be calculated. It is worth noting that the Vector anemometers, in order of height, are Vector A (highest), Vector B, Vector C, Vector D and Vector E (lowest).

5.3.2 Vertical displacement of the airflow for a flow ±15° off the bow

The vertical (K planes) may not coincide exactly with the plane of the anemometer.

For the Vector anemometers mounted on the monkey island, the local planes are:

K24 z= 2.98 m Vectors at z= 2.24 m

The displacements of the Vector anemometers are shown in Table 51 and summarised in Table 52.

location	x (m)	y (m)	z (m)
Vector A	8.35	20.15	2.24
Z_{anemom}	8.34	20.17	2.98
Vector -Z_{anemom}	0.01	-0.02	-0.74
Z_{origin}	201.30	16.99	2.98
Z_{anemom}-Z_{origin}	-192.96	**3.18**	0
Vector B	8.35	19.15	2.24
Z_{anemom}	8.36	19.16	2.98
Vector -Z_{anemom}	-0.01	-0.01	-0.74
Z_{origin}	201.46	15.80	2.98
Z_{anemom}-Z_{origin}	-193.10	**3.36**	0
Vector C	8.35	18.15	2.24
Z_{anemom}	8.36	18.14	2.98
Vector -Z_{anemom}	-0.01	0.01	-0.74
Z_{origin}	201.49	14.48	2.98
Z_{anemom}-Z_{origin}	-193.13	**3.66**	0
Vector D	8.35	17.15	2.24
Z_{anemom}	8.36	17.17	2.98
Vector -Z_{anemom}	-0.01	-0.02	-0.74
Z_{origin}	201.42	13.13	2.98
Z_{anemom}-Z_{origin}	-193.06	**4.04**	0
Vector E	8.35	16.15	2.24
Z_{anemom}	8.35	16.14	2.98
Vector -Z_{anemom}	0.00	0.01	-0.74
Z_{origin}	201.34	11.68	2.98
Z_{anemom}-Z_{origin}	-192.99	**4.46**	0

Table 51 Vertical displacement of the airflow at the Vector anemometer sites on D224.

Vector	A (lowest)	B	C	D	E (lowest)
Displacement (m)	**3.18**	**3.36**	**3.66**	**4.04**	**4.46**

Table 52 Vertical displacements of the air flow at the Vector anemometer sites, in order of instrument height.

5.3.3 Free stream velocities of the airflow for a flow ±15° off the bow

A value of the wind speed in free stream conditions is required to obtain a wind speed error at the anemometer site. The free stream site used is that towards the edge of the tunnel directly abeam of the anemometer site. The free stream velocity is taken to be from the profile at the height the air originated, i.e. the anemometer height minus the amount the air has been raised (Moat *et al.*, 1996). Free stream velocities, taken from the free stream plane, directly abeam of the anemometer site are shown in Table 53.

Anemometer (m)	Free stream velocity (m/s)	Height free stream velocity originated from (m)
Vector A (highest)	14.311	16.99
Vector B	14.240	15.80
Vector C	14.157	14.48
Vector D	14.064	13.13
Vector E (lowest)	13.959	11.68

Table 53 Free stream velocities for each Vector anemometer on D224.

5.3.4 Velocities at the anemometer sites for a flow ±15° off the bow

Figures 53 to 57 show the lines of velocity data through the Vector anemometers 1 to 5 (bridge top). The percentage wind speed error is given by Equation 1.

The results of all anemometer are summarised in Table 54, which also include the values that the airflow has been displaced.

Anemometer	Velocity from each direction (m/s)	Average velocity (m/s)	Free stream velocity (m/s)	% error	Vertical displacement (m)
Vector A	14.714 (x)				
	14.702 (y)	14.710	14.311	2.788	3.18
	14.714 (z)				
Vector B	14.613 (x)				
	14.634 (y)	14.621	14.240	2.676	3.36
	14.616 (z)				
Vector C	14.105 (x)				
	14.552 (y)	14.554	14.157	2.804	3.66
	14.556 (z)				
Vector D	14.475 (x)				
	14.444 (y)	14.468	14.064	2.875	4.04
	14.486 (z)				
Vector E	14.196 (x)				
	14.235 (y)	14.217	13.959	1.848	4.46
	14.219 (z)				

Table 54 Velocity error estimates for the Vector anemometers on D224 (±15°).

5.3.5 Rates of change of velocity at the anemometer sites for a flow ±15° off the bow

This section examines the rate of change of velocity around the anemometer site using Figures 53 to 57. This gives an indication of the accuracy of the wind speed errors and of the suitability of the location for taking wind speed measurements. The rate of change of velocity is given in terms of change per cell and per meter in Table 55.

Anemometer	Velocity data line	Rate of change of velocity per meter (ms^{-1}/m)	Rate of change of velocity per cell ($ms^{-1}/cell$)
Vector A	along (x)	0.056	0.063
	up (y)	0.036	0.027
	across (z)	0.003	0.0013
Vector B	along (x)	0.153	0.096
	up (y)	0.075	0.031
	across (z)	0.010	0.004
Vector C	along (x)	0.201	0.068
	up (y)	0.095	0.037
	across (z)	0.021	0.008
Vector D	along (x)	0.289	0.191
	up (y)	0.157	0.053
	across (z)	0.041	0.162
Vector E	along (x)	0.502	0.351
	up (y)	0.379	0.176
	across (z)	0.091	0.036

Table 55 Rate of change of velocity close to the Vector anemometer sites on D224.

5.4 Wind speed corrections for Discovery D224 OMEGA at ± 30° off the bow

5.4.1 Anemometer locations

The locations of the anemometers sites, in the VECTIS co-ordinate system (where the origin is at the centre of the ship at sea level), are:

Vector A (bridge top)	x=7.48 m, y=20.15 m, z=4.32 m
Vector B (bridge top)	x=7.48 m, y=19.15 m, z=4.32 m
Vector C (bridge top)	x=7.48 m, y=18.15 m, z=4.32 m
Vector D (bridge top)	x=7.48 m, y=17.15 m, z=4.32 m
Vector E (bridge top)	x=7.48 m, y=16.15 m, z=4.32 m

As the anemometers are located on the center line of the ship no effective starboard flow need be calculated. It is worth noting that the Vector anemometers, in order of height, are Vector A (highest), Vector B, Vector C, Vector D and Vector E (lowest).

5.4.2 Vertical displacement of the airflow for a flow ±30° off the bow

For a full description of the method used to calculate the vertical displacement of the air and the free stream height, refer to Moat *et al*., (1996)

The vertical (K planes) may not coincide exactly with the plane of the anemometer.

For the Vector anemometers mounted on the monkey island, the local planes are:

K24 z= 4.10 m Vectors at z= 4.32 m

The displacements of the Vector anemometers are shown in Table 56 and summarised in Table 57.

location	x (m)	y (m)	z (m)
Vector A	7.48	20.15	4.32
Z_{anemom}	7.47	20.11	4.10
Vector -Z_{anemom}	0.01	0.04	0.22
Z_{origin}	246.24	15.76	4.10
Z_{anemom}-Z_{origin}	-238.77	**4.35**	0
Vector B	7.48	19.15	4.32
Z_{anemom}	7.47	19.16	4.10
Vector -Z_{anemom}	0.01	-0.01	0.22
Z_{origin}	246.01	14.40	4.10
Z_{anemom}-Z_{origin}	-238.54	**4.76**	0
Vector C	7.48	18.15	4.32
Z_{anemom}	7.48	18.16	4.10
Vector -Z_{anemom}	0.00	-0.01	0.22
Z_{origin}	245.89	12.91	4.10
Z_{anemom}-Z_{origin}	-238.41	**5.25**	0
Vector D	7.48	17.15	4.32
Z_{anemom}	7.47	17.17	4.10
Vector -Z_{anemom}	0.01	-0.02	0.22
Z_{origin}	245.78	11.43	4.10
Z_{anemom}-Z_{origin}	-238.31	**5.74**	0
Vector E	7.48	16.15	4.32
Z_{anemom}	7.48	16.18	4.10
Vector -Z_{anemom}	0.00	-0.03	0.22
Z_{origin}	245.69	9.92	4.10
Z_{anemom}-Z_{origin}	-238.21	**6.26**	0

Table 56 Vertical displacement of the airflow at the Vector anemometer sites on D224.

Vector	A (highest)	B	C	D	E (lowest)
Displacement (m)	**4.35**	**4.76**	**5.25**	**5.74**	**6.26**

Table 57 Vertical displacements of the air flow at the Vector anemometer sites, in order of instrument height.

5.4.3 Free stream velocities for a flow ±30° off the bow

A value of the wind speed in free stream conditions is required to obtain a wind speed error at the anemometer site. The free stream site used is that towards the edge of the tunnel directly abeam of the anemometer site. The free stream velocity is taken to be from the profile at the height the air originated, i.e. the anemometer height minus the amount the air has been raised (Moat *et al.*, 1996). Free stream velocities, taken from the free stream plane, directly abeam of the anemometer site are shown in Table 58.

Anemometer (m)	Free stream velocity (m/s)	Height free stream velocity originated from (m)
Vector A (highest)	14.226	15.76
Vector B	14.138	14.40
Vector C	14.036	12.91
Vector D	13.925	11.43
Vector E (lowest)	13.796	9.92

Table 58 Free stream velocities for each Vector anemometer on D224.

5.4.4 Velocities at the anemometer sites for a flow ±30° off the bow

Figures 58 to 62 show the lines of velocity data through the Vector anemometers A to E (Monkey Island). The percentage wind speed error is given by Equation 1.

The results of all anemometer are summarised in Table 59, which also include the values that the airflow has been displaced.

Anemometer	Velocity from each direction (m/s)	Average velocity (m/s)	Free stream velocity (m/s)	% error	Vertical displacement (m)
Vector A	15.058 (x)				
	15.066 (y)	15.593	14.226	5.858	4.35
	15.054 (z)				
Vector B	15.060 (x)				
	15.044 (y)	15.054	14.138	6.479	4.76
	15.058 (z)				
Vector C	14.997 (x)				
	15.003 (y)	15.001	14.036	6.878	5.25
	15.004 (z)				
Vector D	14.965 (x)				
	14.918 (y)	14.956	13.925	7.402	5.74
	14.984 (z)				
Vector E	14.748 (x)				
	14.743(y)	14.746	13.796	6.882	6.26
	14.816 (z)				

Table 59 Velocity error estimates at the Vector anemometer sites on D224 (±30°)

5.4.5 Rates of change of velocity at the anemometer sites for a flow ±30° off the bow

This section examines the rate of change of velocity around the anemometer site using Figures 58 to 62. This gives an indication of the accuracy of the wind speed errors and of the suitability of the location for taking wind speed measurements. The rate of change of velocity is given in terms of change per cell and per meter in Table 60.

Anemometer	Velocity data line	Rate of change of velocity per meter (ms^{-1}/m)	Rate of change of velocity per cell ($ms^{-1}/cell$)
Vector A	along (x)	0.103	0.118
	up (y)	0.022	0.015
	across (z)	0.000	0.0014
Vector B	along (x)	0.116	0.130
	up (y)	0.028	0.019
	across (z)	0.009	0.011
Vector C	along (x)	0.171	0.190
	up (y)	0.062	0.046
	across (z)	0.038	0.039
Vector D	along (x)	0.649	0.271
	up (y)	0.129	0.061
	across (z)	0.092	0.088
Vector E	along (x)	0.387	0.433
	up (y)	0.332	0.190
	across (z)	0.227	0.260

Table 60 Rate of change of velocity close to the Vector anemometer sites on D224.

The Vector anemometers are mounted in a region of high airflow distortion and are intended for validation of the CFD package and are not used for wind stress calculation.

5.5 Conclusions

The Vector anemometers mounted above the bridge are in a region of high airflow disturbance. Across all five Vector anemometers the rate of change of velocity typically reads below 0.2 ms^{-1}/m. Velocity estimates range from a large underestimate of 6.8% to 0.7% (head to wind), to an overestimate of 4.5% to 6.0% at ±15° and a 5.8% to 7.4% increase at ±30°.

6. Summary

The foremast and main mast anemometers are in well exposed locations and can be used for accurate meteorological measurements. In contrast the Vector anemometer sites are located in region of high airflow distortion. The results are summarised here and tabulated for VIVALDI (Tables 61 and 62) and OMEGA (Table 61 and 63).

The anemometer sites on the foremast have small wind speed errors for flows within ±30° off the bow (Figure 63a). Errors of less than 5% are predicted for flows within ±30° off the bow. It must be noted that the ship presents less of an obstruction to the airflow when directly head to wind, and consequently errors of less than 2% are predicted for flows within ±15° off the bow. The wind speed errors at the main mast anemometer site are larger, typically between 4% to 6%. Even so the anemometer is positioned at such a height that the rates of change of velocity are as small as those predicted for the foremast instruments. The vertical displacement of the airflow also increases with relative wind direction off the bow (Figure 63b). The air is displaced vertically by approximately 1 to 2 m before it reaches the foremast anemometer sites. This increases to roughly 2 to 4 m for the main mast sonic anemometer.

R.R.S. Discovery cruise D223 and D224								
Wind dirn (°)	research sonic		Wind Master sonic		Young AQ		main mast research sonic	
	ΔU (%)	Δz (m)	ΔU (%)	Δz (m)	ΔU (%)	Δz (m)	ΔU (%)	Δz (m)
-30	4.08	1.52	1.49	1.79	2.15	1.77	6.07	3.69
-15	1.29	1.21	-0.05	1.48	0.33	1.44	4.55	2.70
0	-0.40	1.06	-0.57	1.09	-0.39	1.04	3.76	2.32
15	0.32	1.43	1.33	1.25	1.39	1.22	4.21	2.87
30	2.06	1.79	4.23	1.49	4.22	1.55	4.88	3.58

Table 61 Variation of percentage velocity error (ΔU) and vertical displacement (Δz) wind direction on *R.R.S. Discovery* cruise D223 and D224.

The *Vector mas*t on VIVALDI and OMEGA were purposely positioned in regions of large rates of change of velocity. This was done to gather data to perform a validation of the VECTIS CFD code. The Vector anemometers positioned on the lifeboat deck (VIVALDI) experienced large decelerations in wind speed of up to 15% for flows directly over the bow (Figure 64a). The size of the velocity errors steadily reduced to zero then changed sign and became a wind speed increase of between 5% to 10% at ±30°. The *Vector mast* was then moved to the bridge top on OMEGA and, for flows directly over the bow, the decelerations experienced by the anemometers were not as severe (Figure 65a). On the other hand the anemometers at ±15° experience an increase in wind speed of up to 2%, unlike the decrease observed at the VIVALDI Vector anemometer sites. The vertical displacements at the OMEGA Vector sites are larger (Figure 65b). The airflow was raised by roughly 3m to 6m on the OMEGA cruise. This was over 1m more than the airflow at the lifeboat deck on the VIVALDI cruise.

R.R.S. Discovery cruise D223 VIVALDI										
Wind dirn (°)	Vector A (highest)		Vector B		Vector C		Vector D		Vector E (lowest)	
	ΔU (%)	Δz (m)	ΔU (%)	Δz (m)	ΔU (%)	Δz (m)	ΔU (%)	Δz (m)	ΔU (%)	Δz (m)
-30	4.57	2.91	5.00	2.86	5.57	3.05	6.04	3.30	5.92	3.58
-15	-	-	-3.89	1.56	-3.32	1.65	-3.57	1.83	-7.41	1.79
0	-6.85	1.61	-8.13	1.61	-14.02	1.60	-15.79	1.49	-15.59	1.41
15	-0.79	2.53	-1.21	2.73	-1.29	2.95	-1.72	3.18	-6.45	3.55
30	3.19	3.34	3.51	3.59	9.69	3.90	4.52	4.30	5.35	4.83

Table 62 Variation of percentage velocity error (ΔU) and vertical displacement (Δz) wind direction for the Vector anemometers on *R.R.S. Discovery* cruise D223.

R.R.S. Discovery cruise D224 OMEGA										
Wind dirn (deg)	Vector A (highest)		Vector B		Vector C		Vector D		Vector E (lowest)	
	ΔU (%)	Δz (m)	ΔU (%)	Δz (m)	ΔU (%)	Δz (m)	ΔU (%)	Δz (m)	ΔU (%)	Δz (m)
0	-0.72	2.54	-3.29	2.75	-2.67	2.77	-6.06	2.72	-6.89	3.11
±15	2.79	3.18	2.68	3.36	2.80	3.66	2.88	4.04	1.85	4.46
±30	5.86	4.35	6.48	4.76	6.88	5.25	7.40	5.74	6.88	6.26

Table 63 Variation of percentage velocity error (ΔU) and vertical displacement (Δz) wind direction for the Vector anemometers on *R.S.S. Discovery* cruise D224.

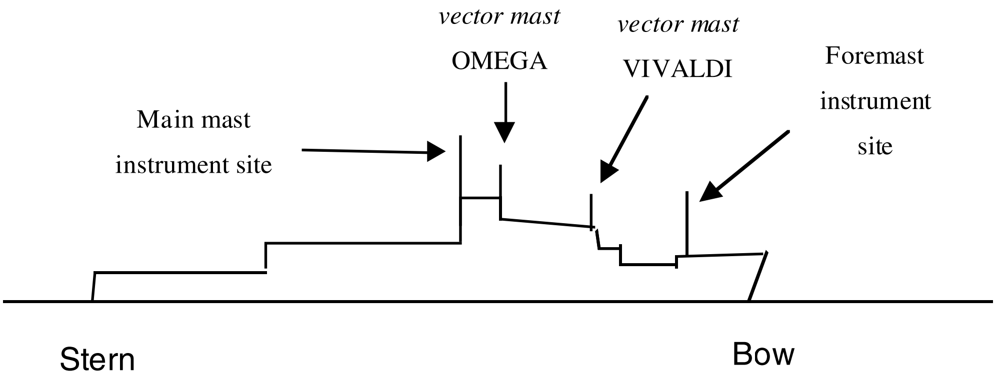
In conclusion, we have predicted the airflow distortion at a number of anemometer sites on the *R.R.S. Discovery* at a number of relative wind directions. Future work will use the CFD results contained in this report to examine the validity of VECTIS to predict the airflow distortion over research ships.

7. References

Moat, B. I. and M. J. Yelland, 1997: Airflow 15 and 30 degrees off the bow of the *R.R.S. Discovery*: the disturbance of the flow at anemometer sites for cruises D199-D201 and D213-D214. Southampton Oceanography Centre, U.K. *SOC Internal Report No. 25*. 43 pp.

Moat, B. I, M. J. Yelland. and J. Hutchings, 1996: Airflow over the *R.R.S. Discovery* using the Computational Fluid Dynamics package VECTIS, Southampton Oceanography Centre, Southampton. U.K. *SOC Internal Report No. 2*. 41 pp.

8. Figures



Scale 1:1000 **Profile view of the *R.R.S. Discovery***

Figure 1 The locations of the instrumentation sites on *R.R.S. Discovery*.

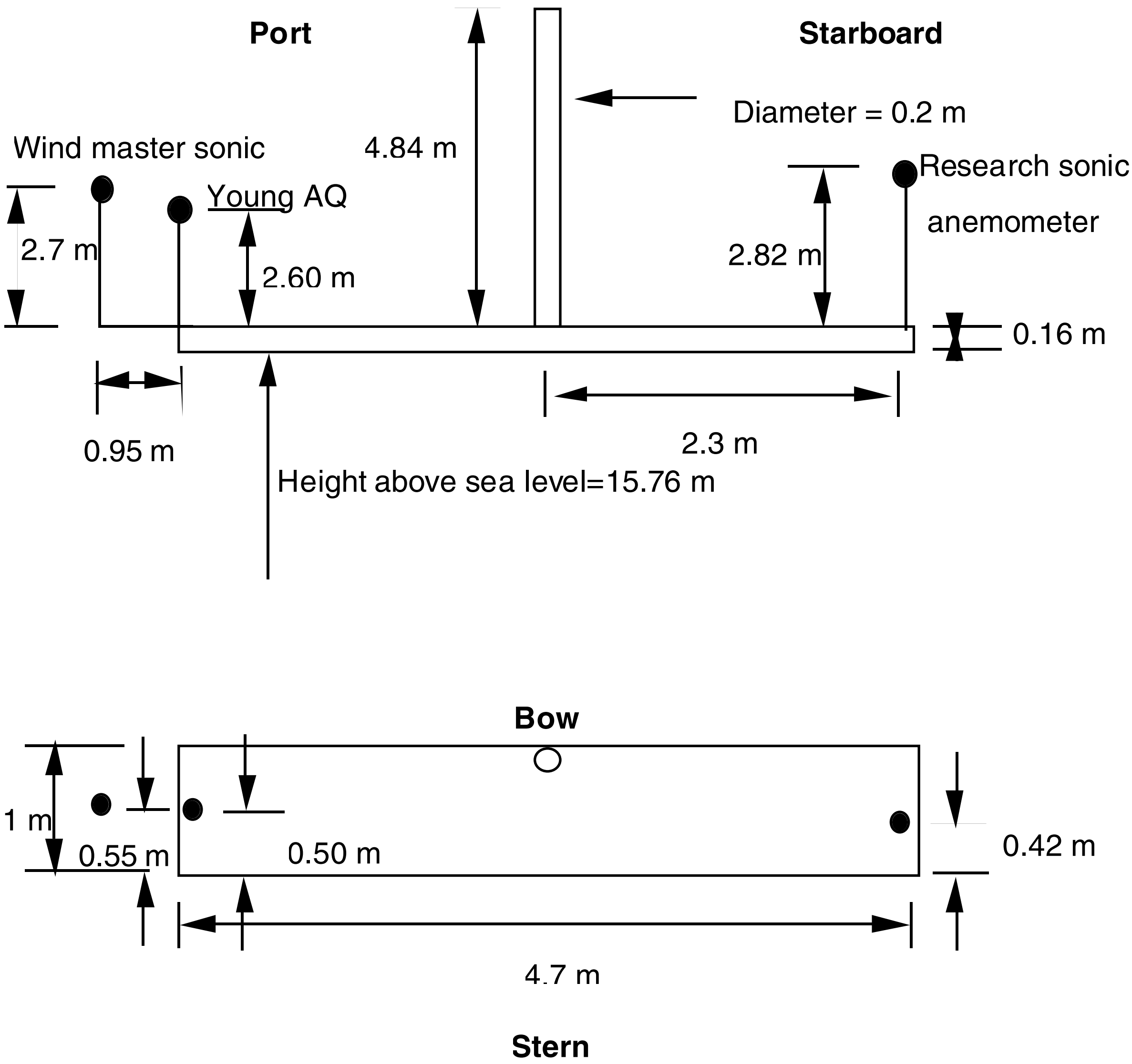


Figure 2 a) The locations of the foremast anemometers on *R.R.S. Discovery* cruises VIVALDI and OMEGA.

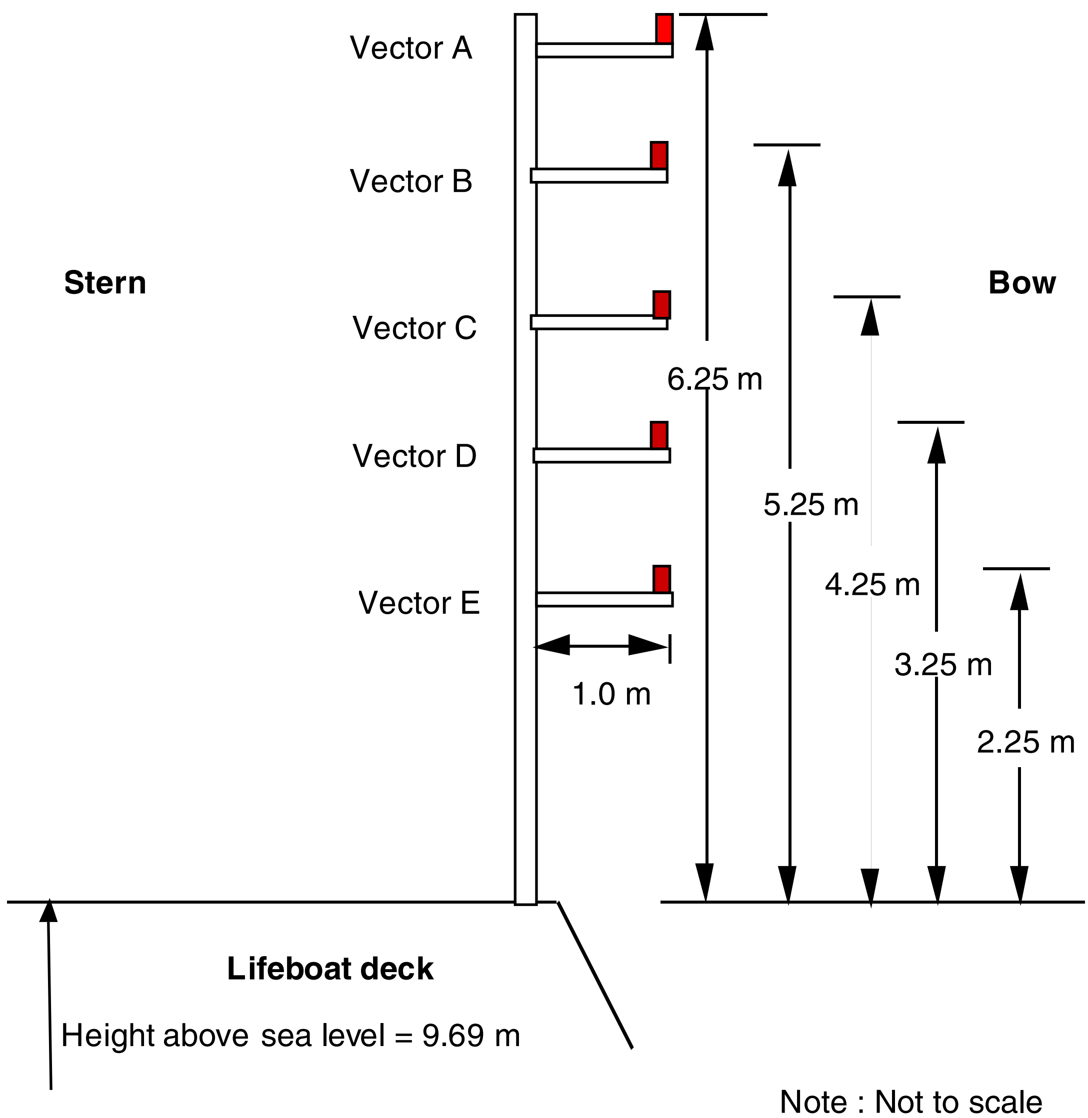


Figure 2 b) The locations of the Vector anemometers on *R.R.S. Discovery* cruise D223 (VIVALDI).

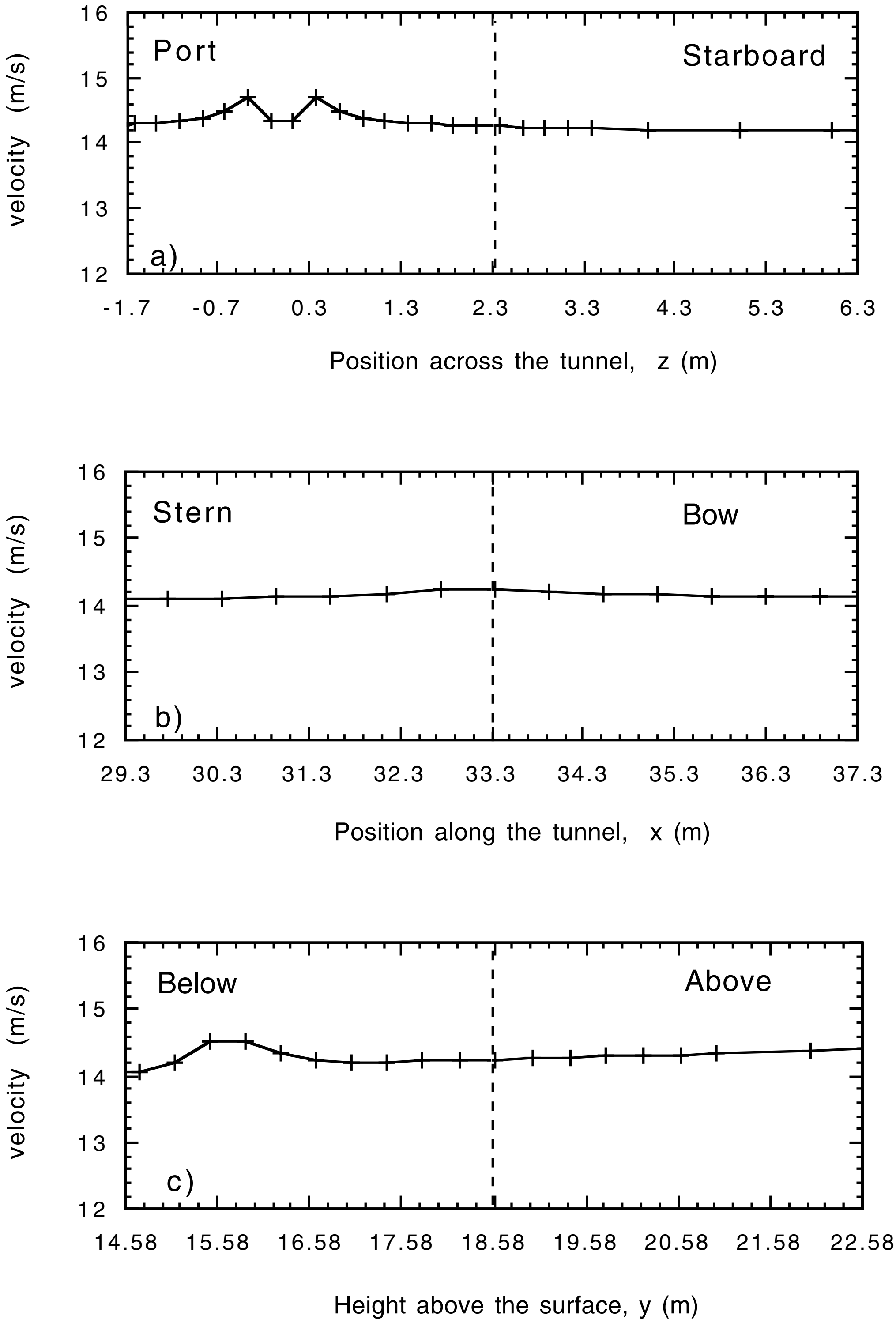


Figure 3 Lines of velocity data through the research sonic anemometer position (indicated by the dashed line) in all three directions; a) across the tunnel (z), b) along the tunnel (x) and c) vertically (y). Results are from a bow-on flow (head to wind) for cruises D223-D224.

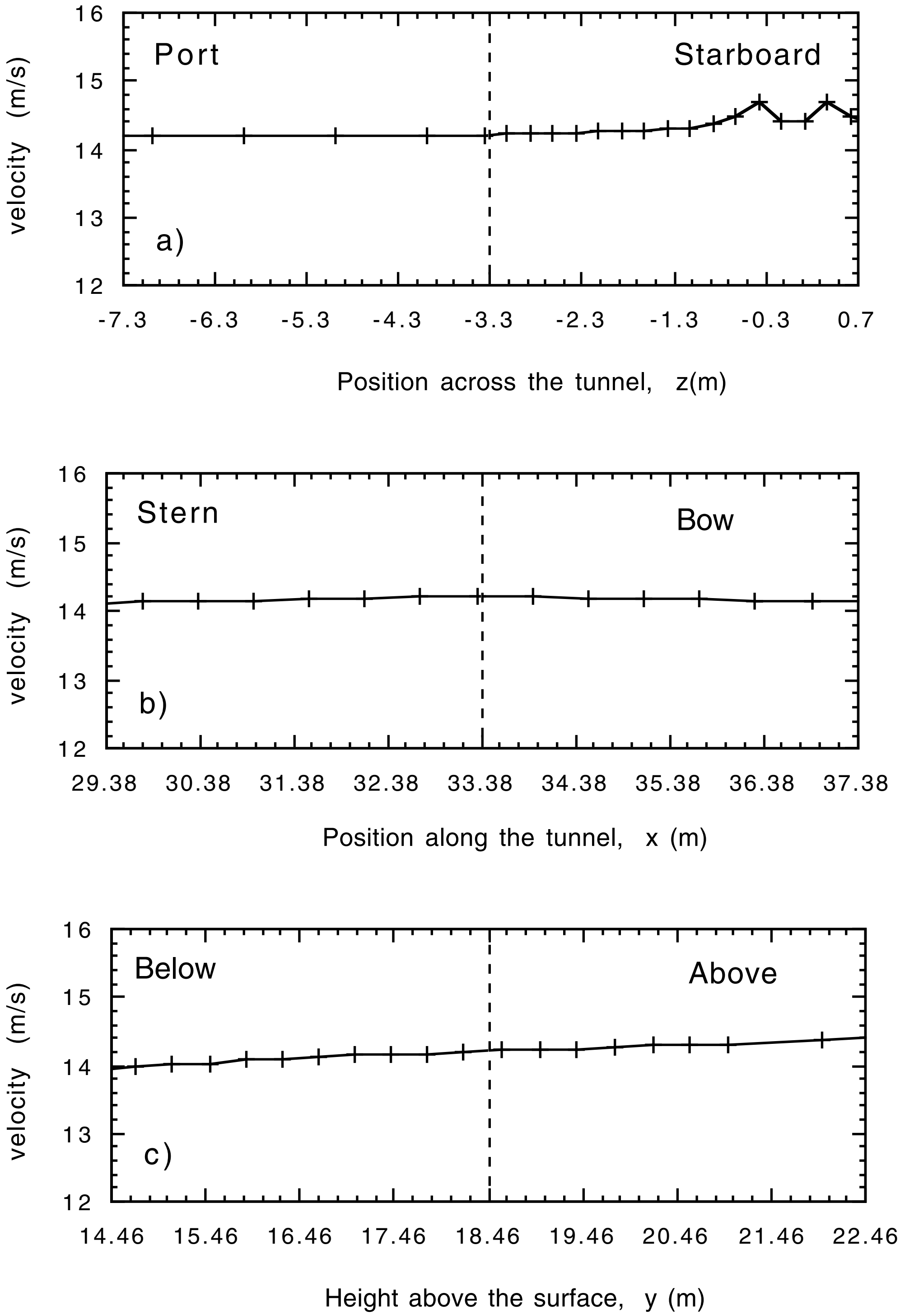


Figure 4 As for Figure 3, but for the Wind Master sonic anemometer.

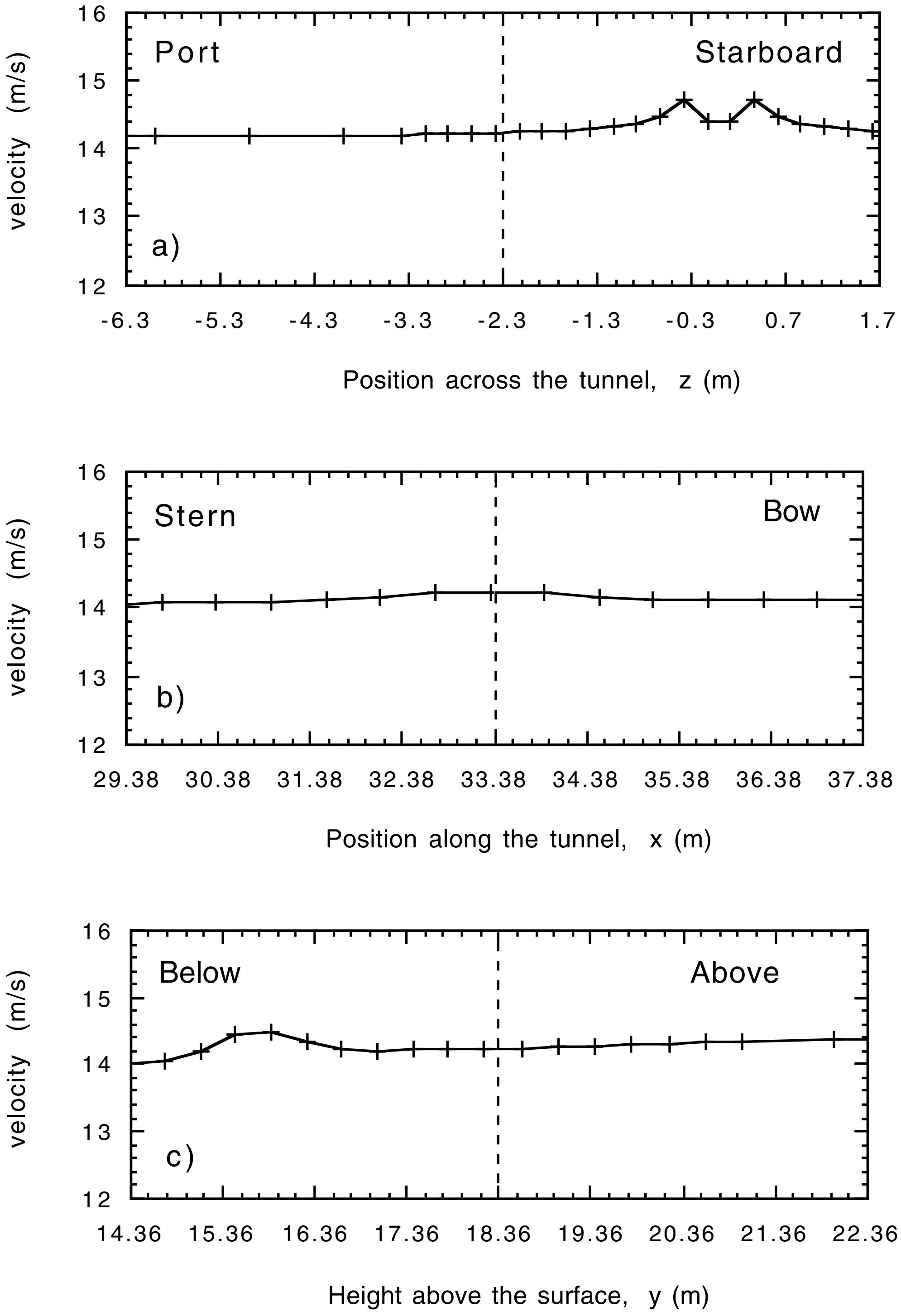


Figure 5 As for Figure 3, but for the Young AQ anemometer.

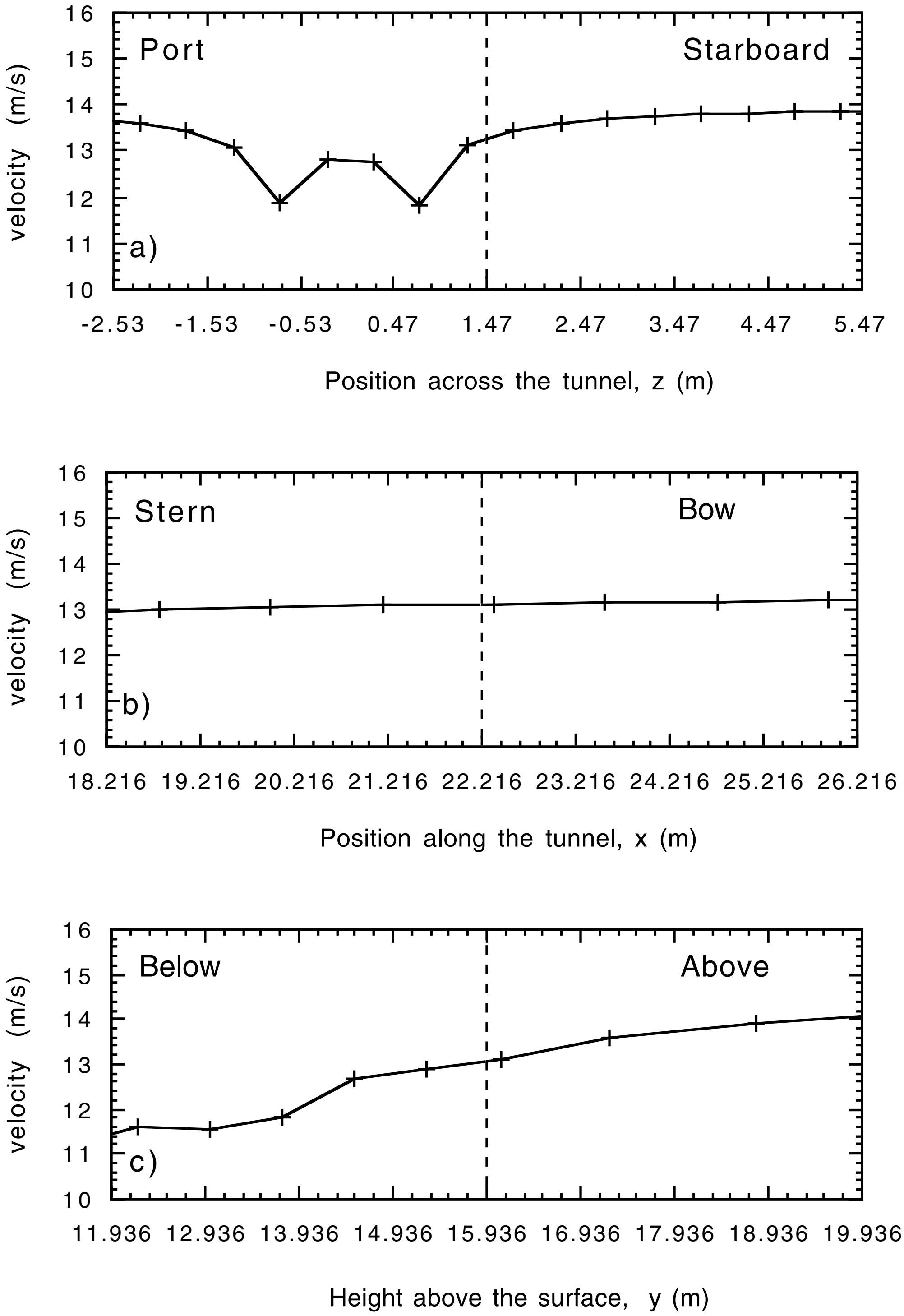


Figure 6 Lines of velocity data through the Vector A (highest) anemometer position (indicated by the dashed line) in all three directions; a) across the tunnel (z), b) along the tunnel (x) and c) vertically (y). Results are from a bow-on flow (head to wind) for cruises D223.

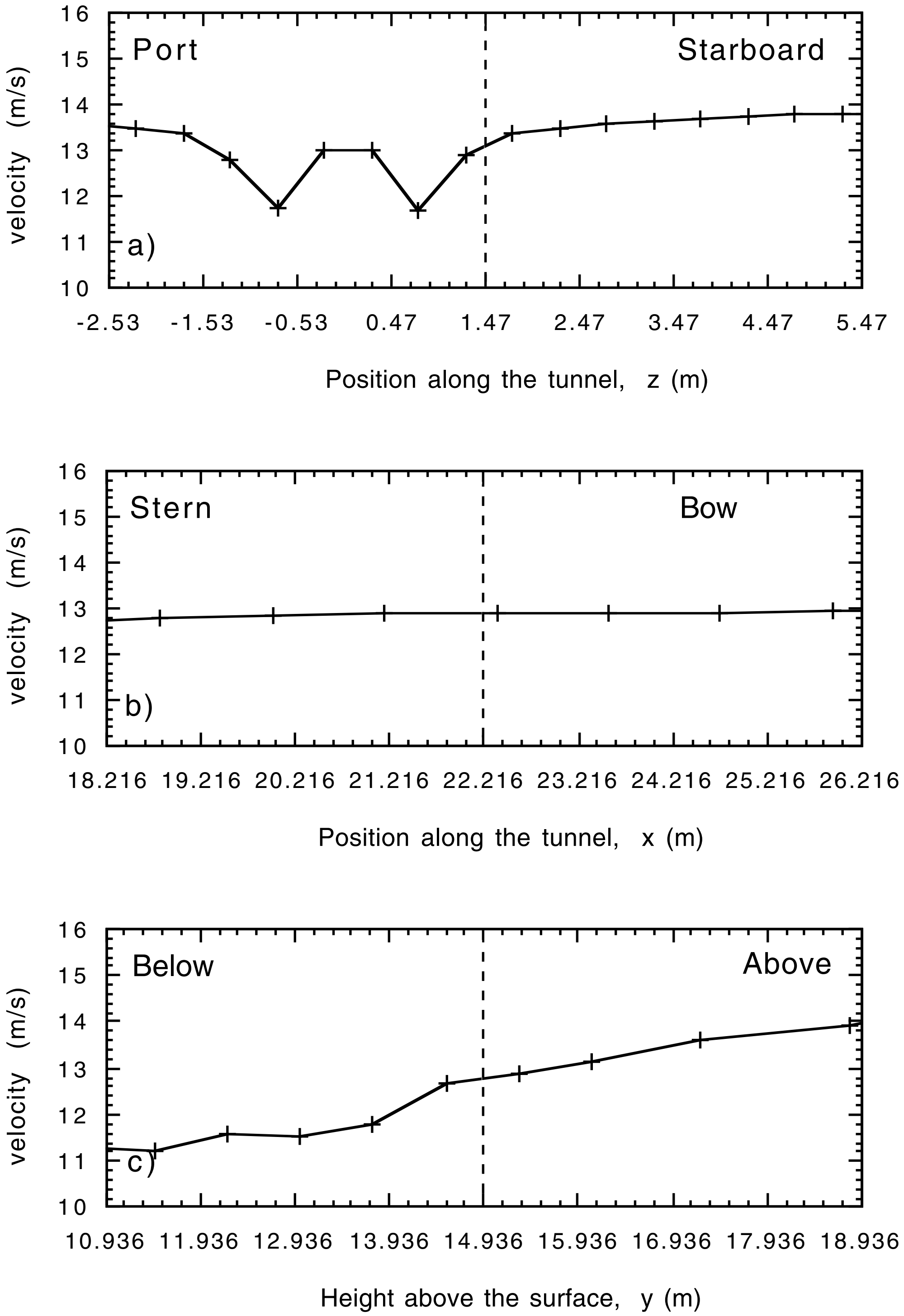


Figure 7 As for Figure 6, but for the Vector B anemometer.

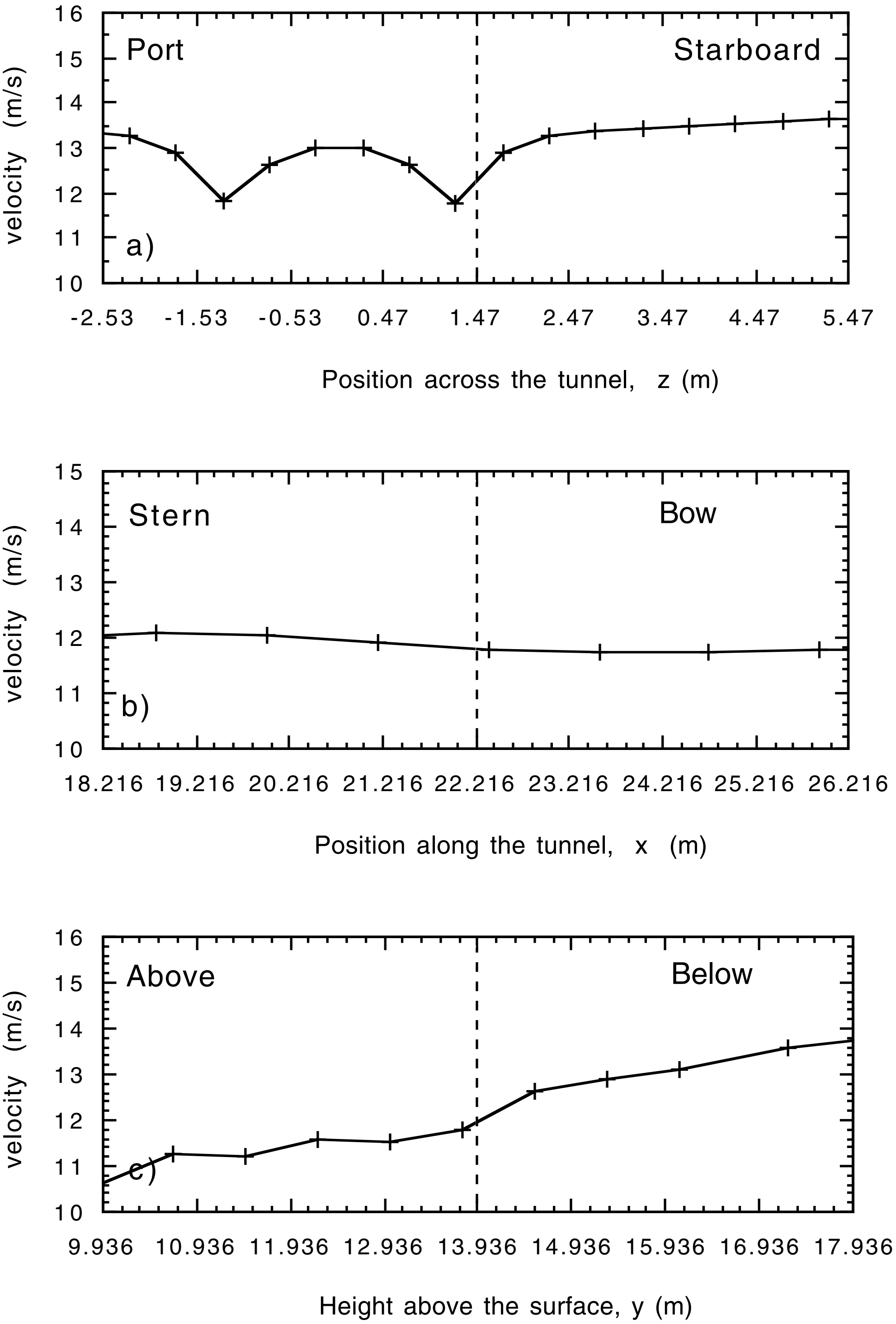


Figure 8 As for Figure 6, but for the Vector C anemometer.

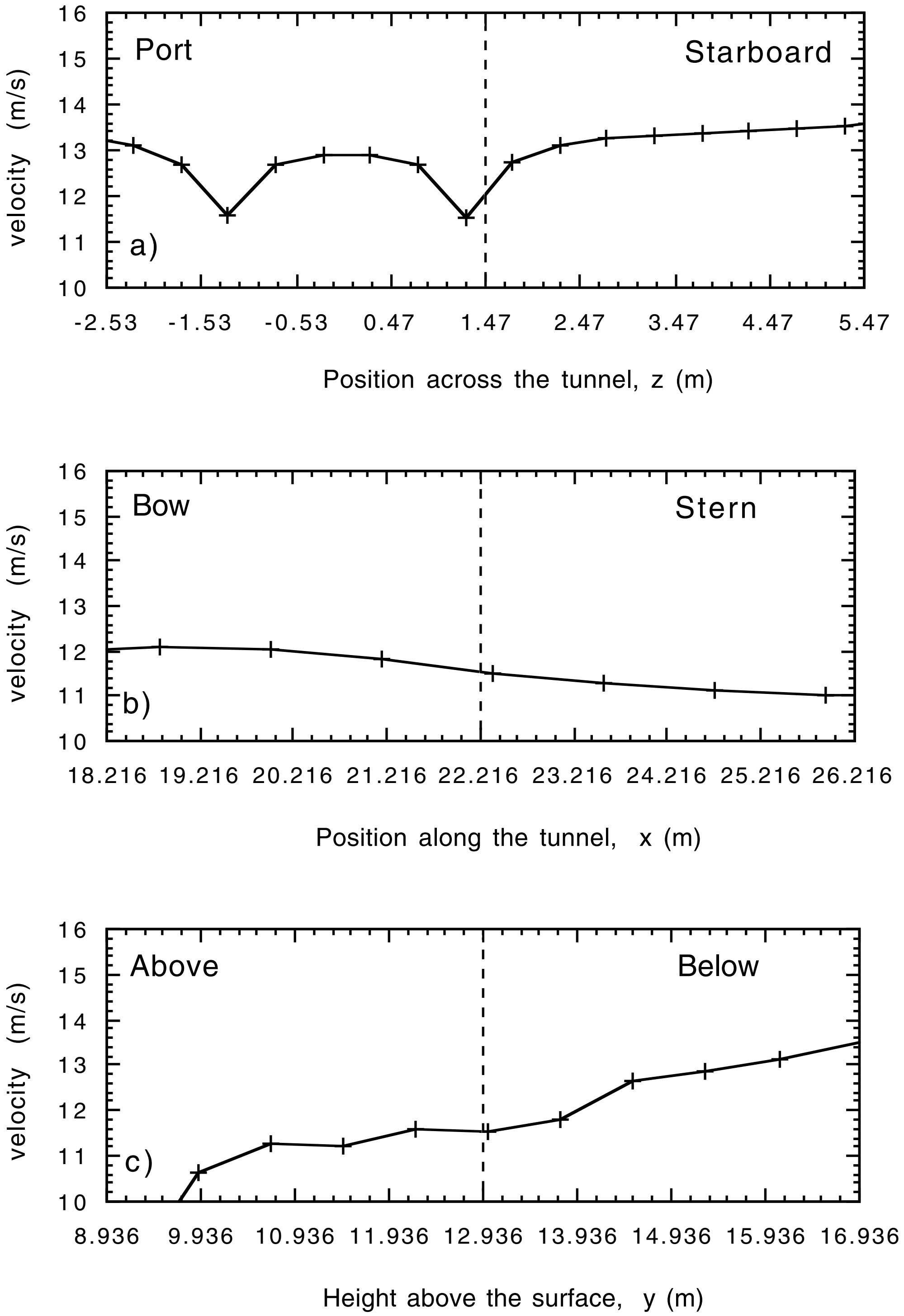


Figure 9 As for Figure 6, but for the Vector D anemometer.

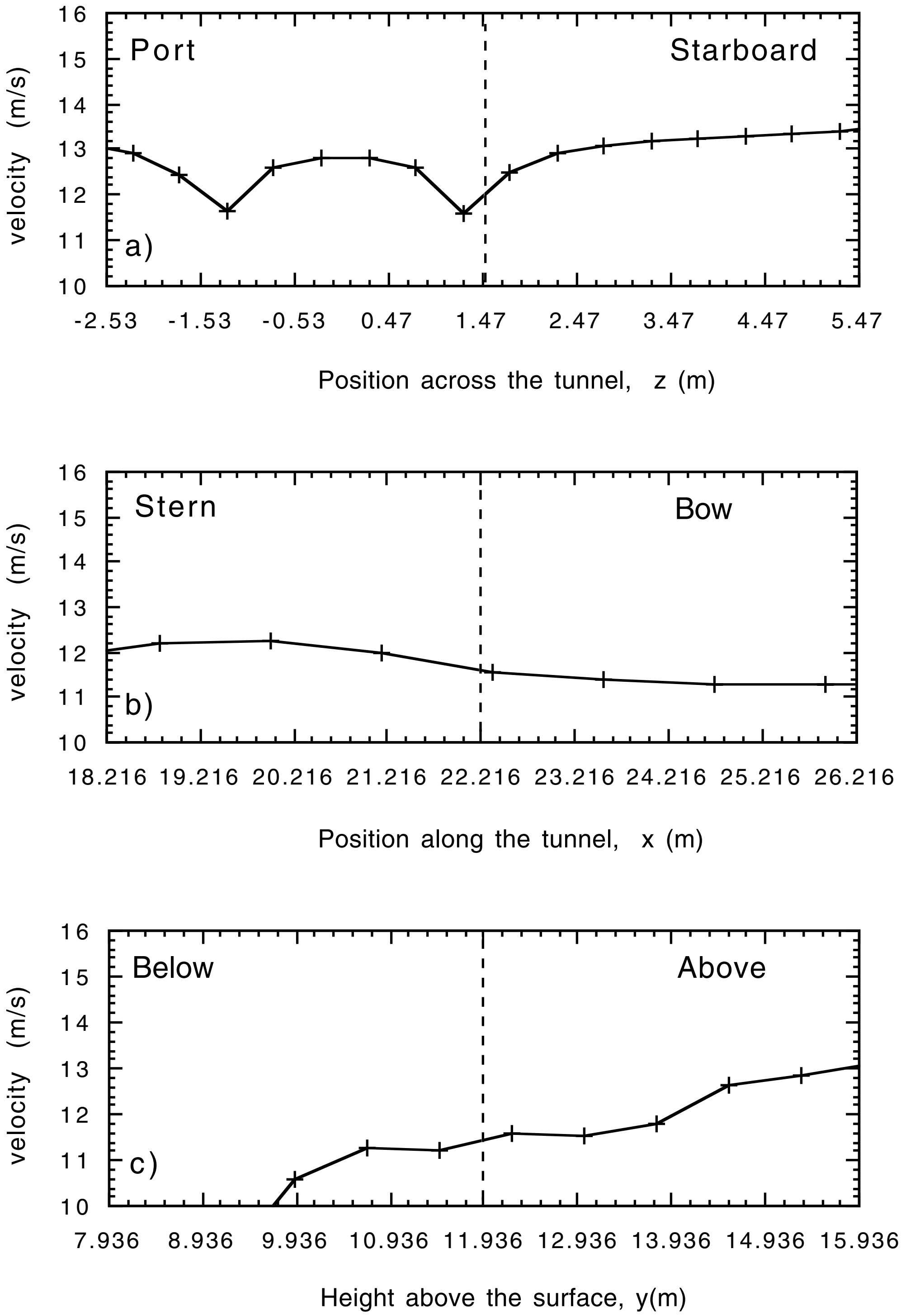


Figure 10 As for Figure 6, but for the Vector E (lowest) anemometer.

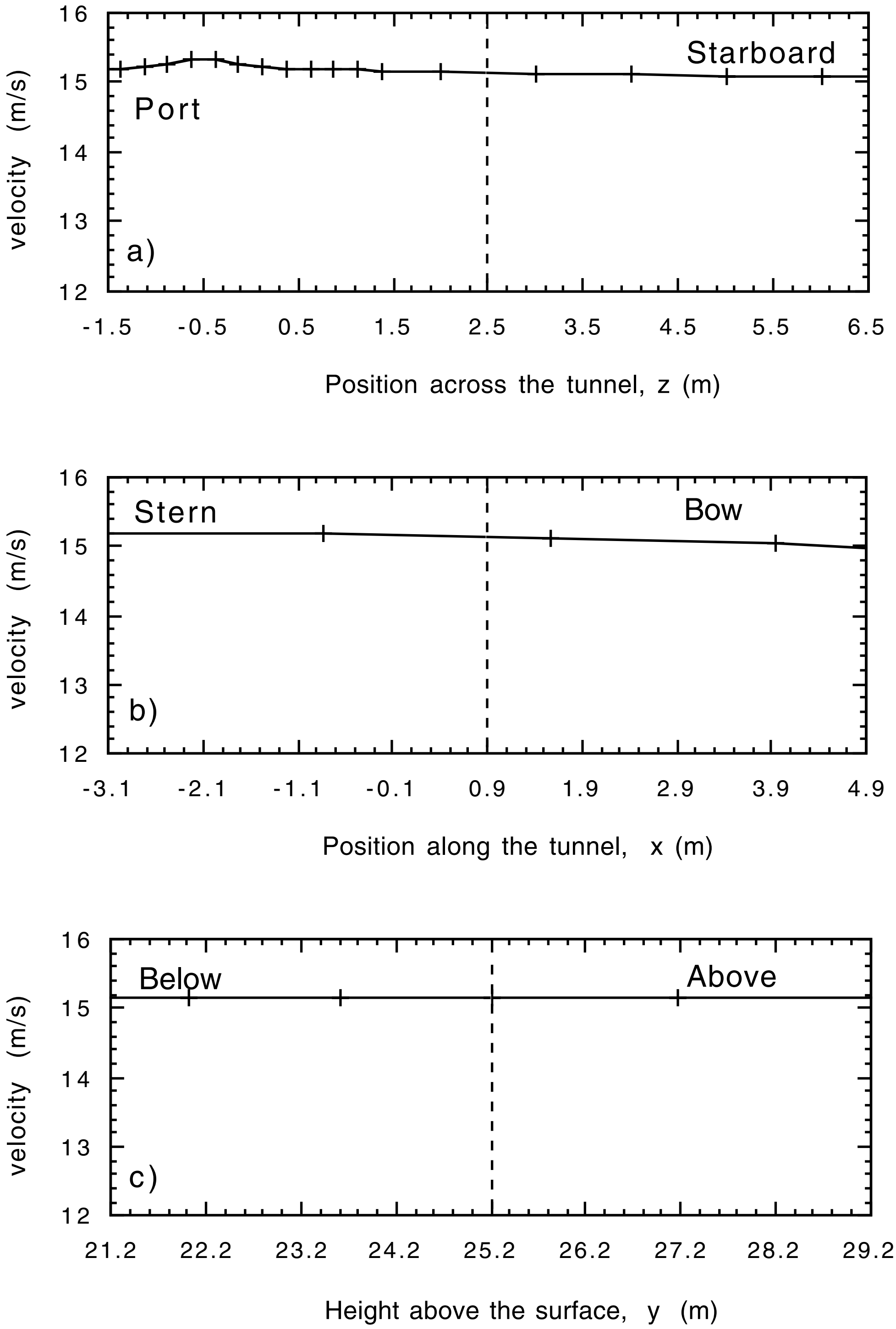


Figure 11 As Figure 3, but for the main mast research sonic anemometer.

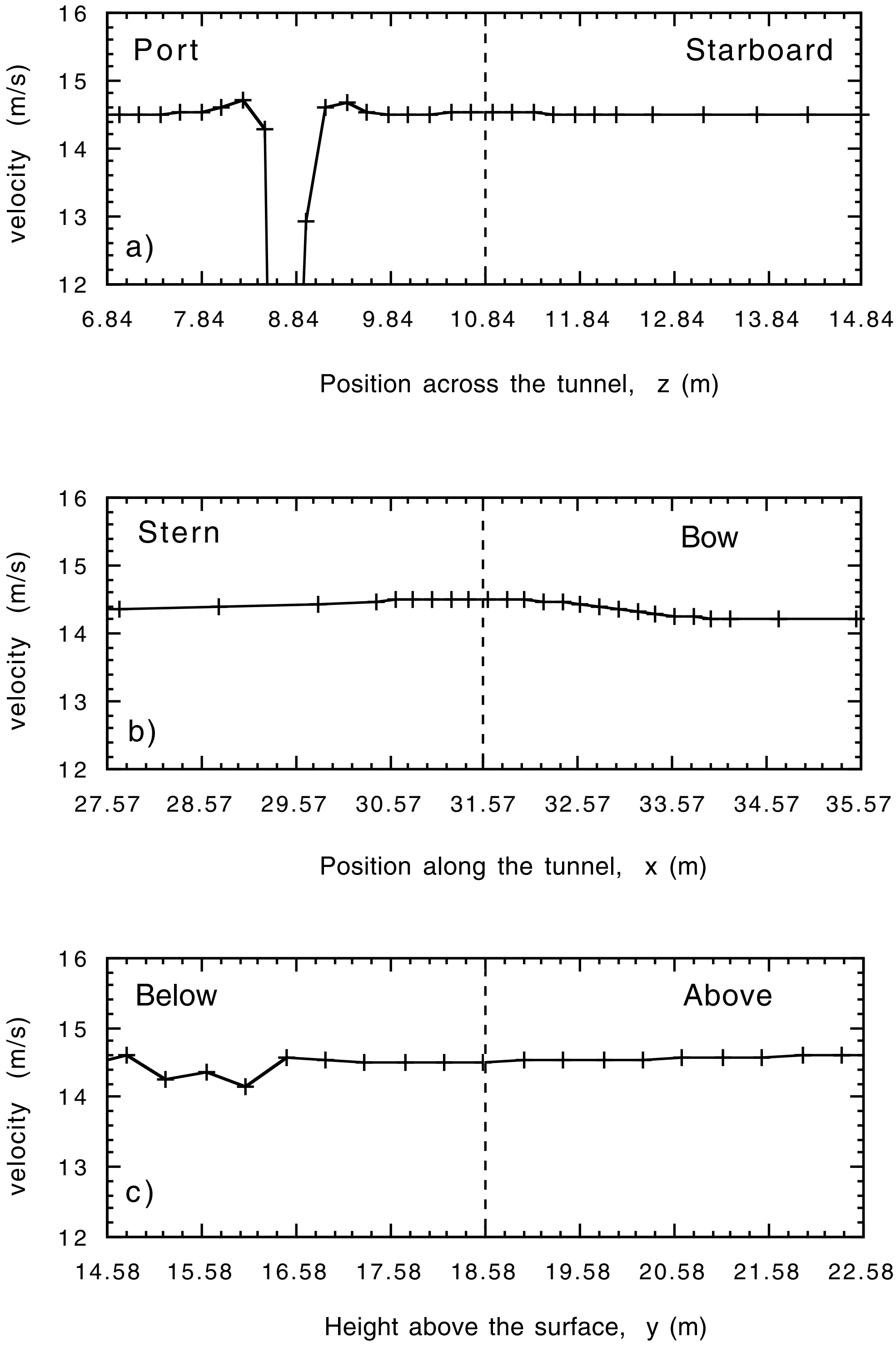


Figure 12 Lines of velocity data through the research sonic anemometer position (indicated by the dashed line) in all three directions; a) across the tunnel (z), b) along the tunnel (x) and c) vertically (y). Results are from a 15° flow over the port bow for cruises D223-D224.

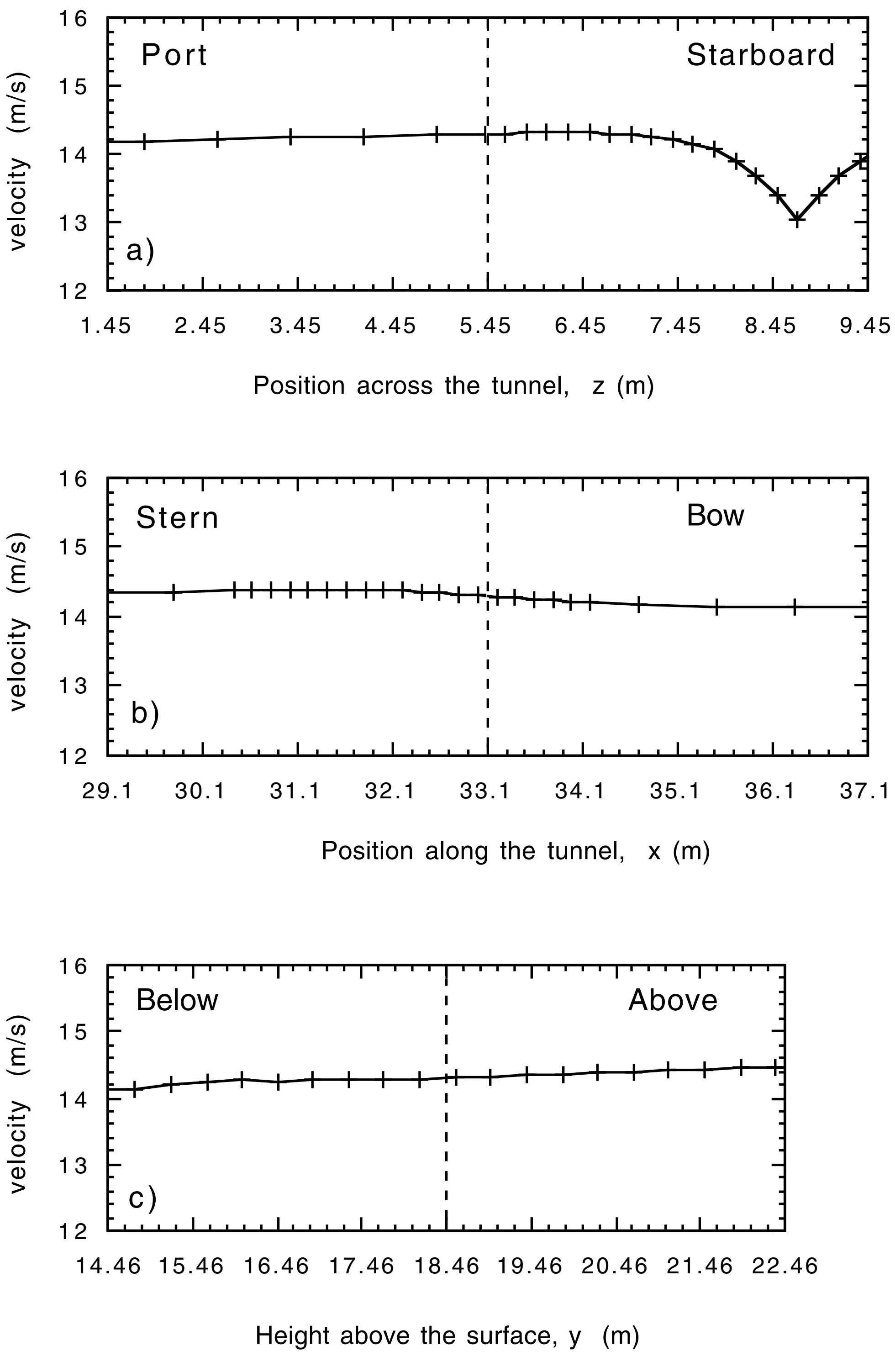


Figure 13 As Figure 12, but for the Wind Master sonic anemometer.

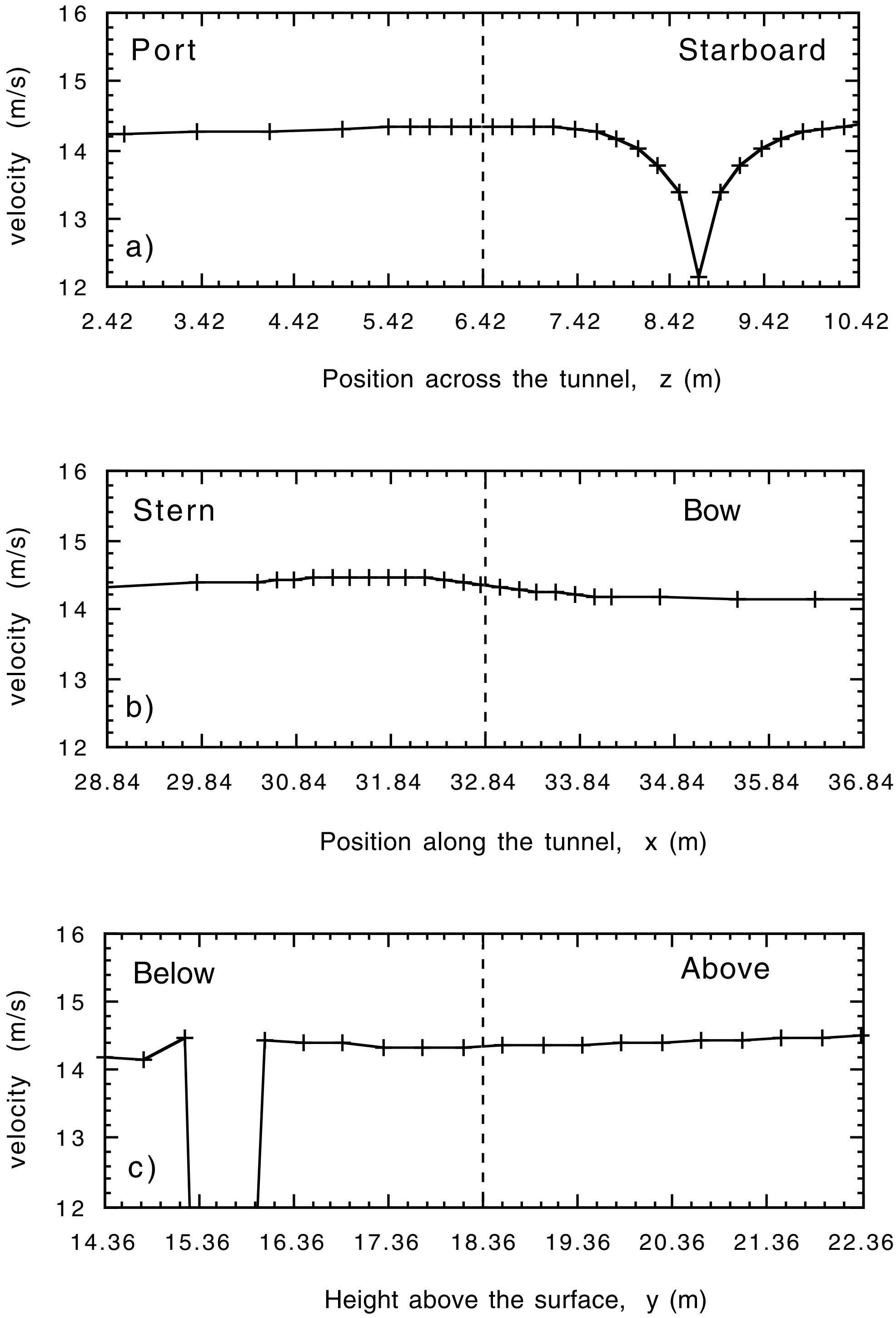


Figure 14 As Figure 12, but for the Young AQ anemometer.

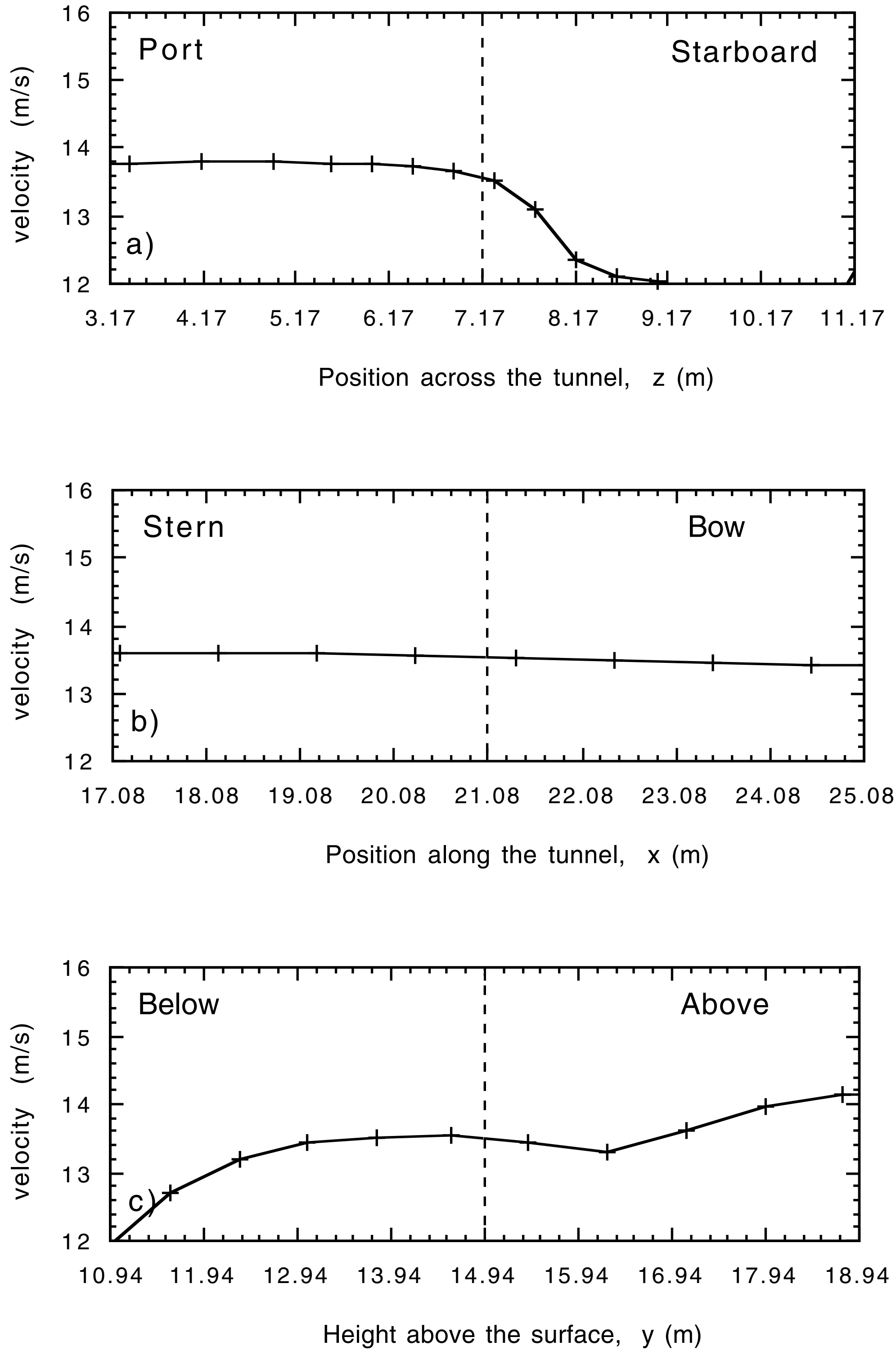


Figure 15 Lines of velocity data through the Vector B anemometer position (indicated by the dashed line) in all three directions; a) across the tunnel (z), b) along the tunnel (x) and c) vertically (y). Results are from a 15° flow over the port bow for cruise D223.

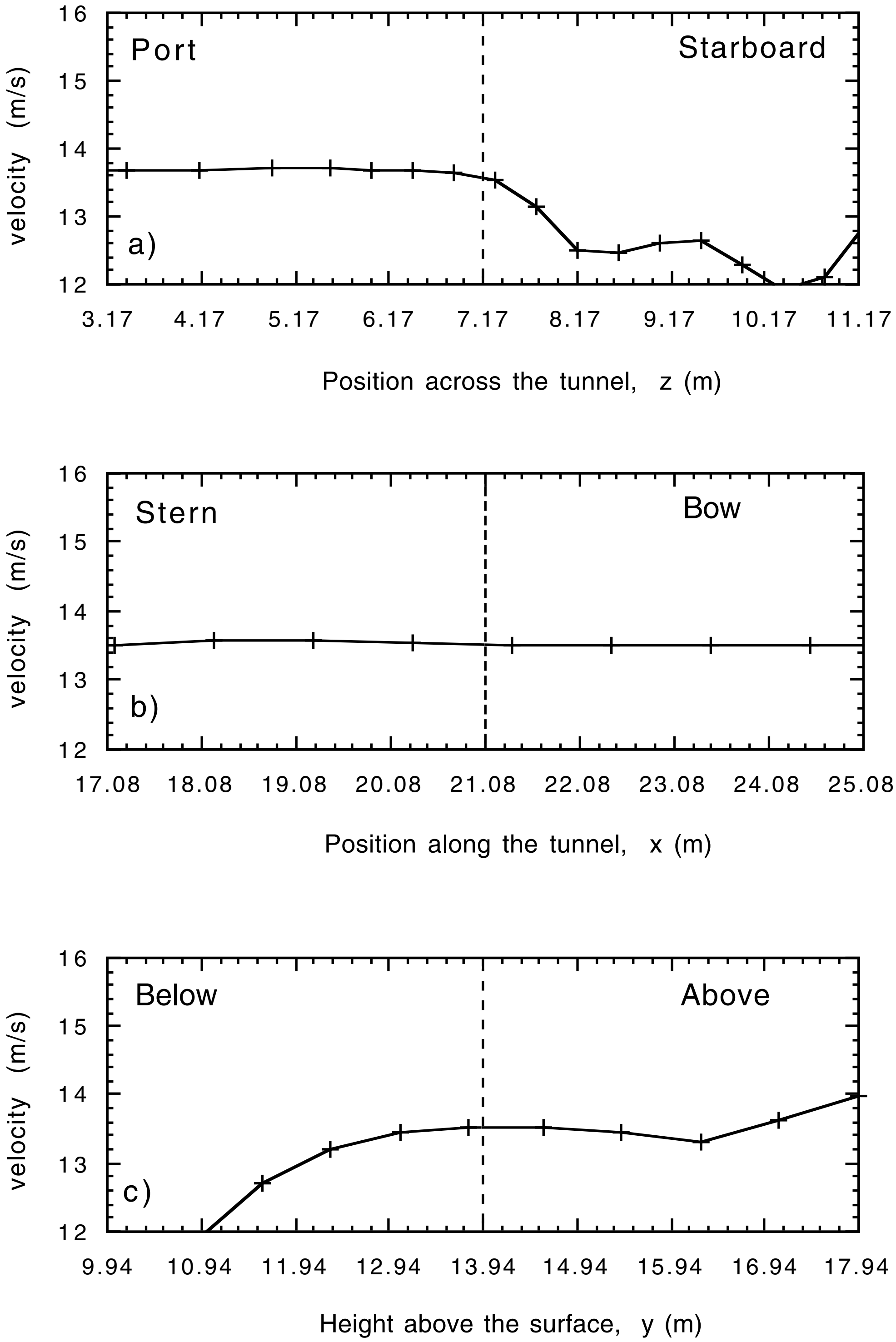


Figure 16 As Figure 15, but for the Vector C anemometer.

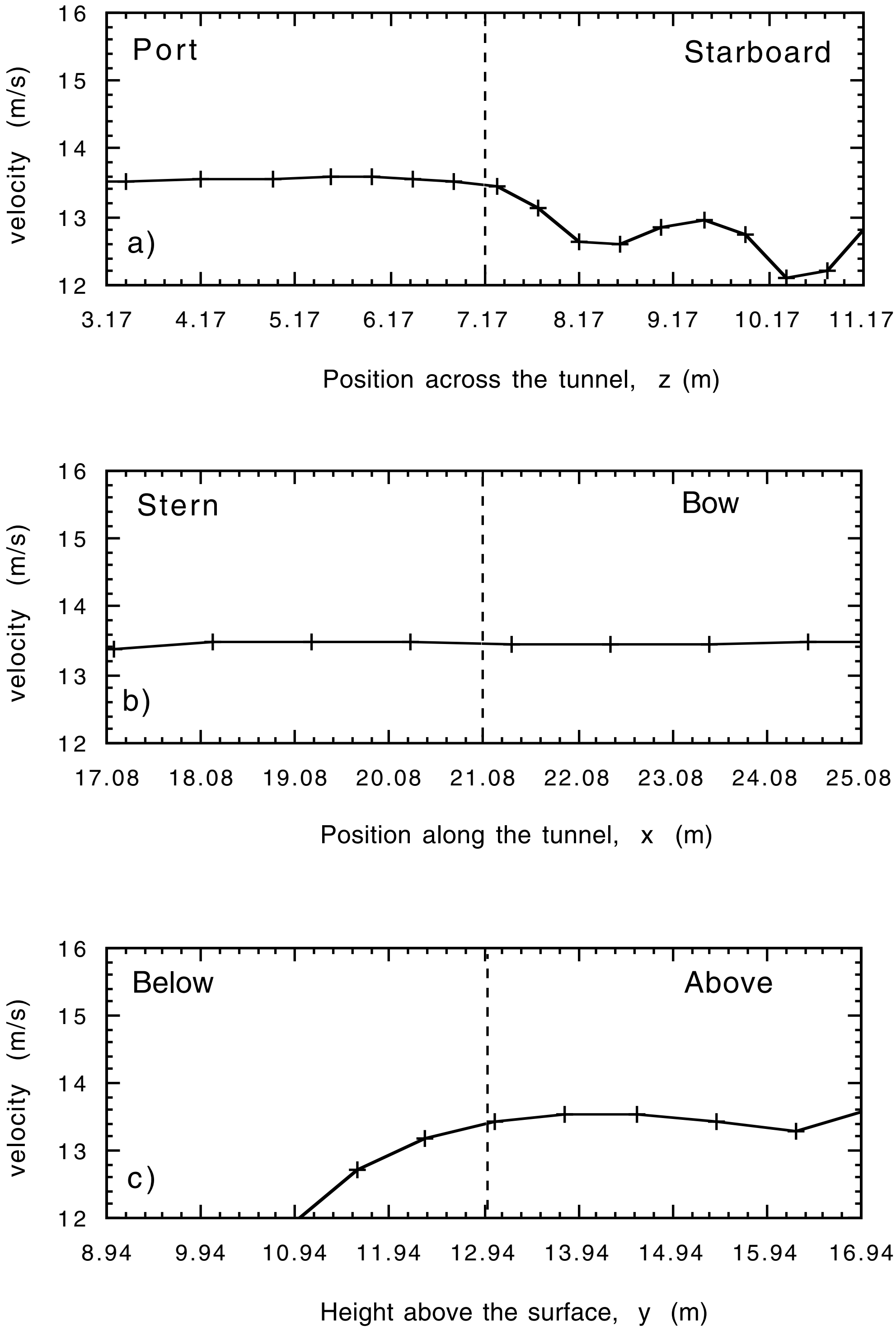


Figure 17 As Figure 15, but for the Vector D anemometer.

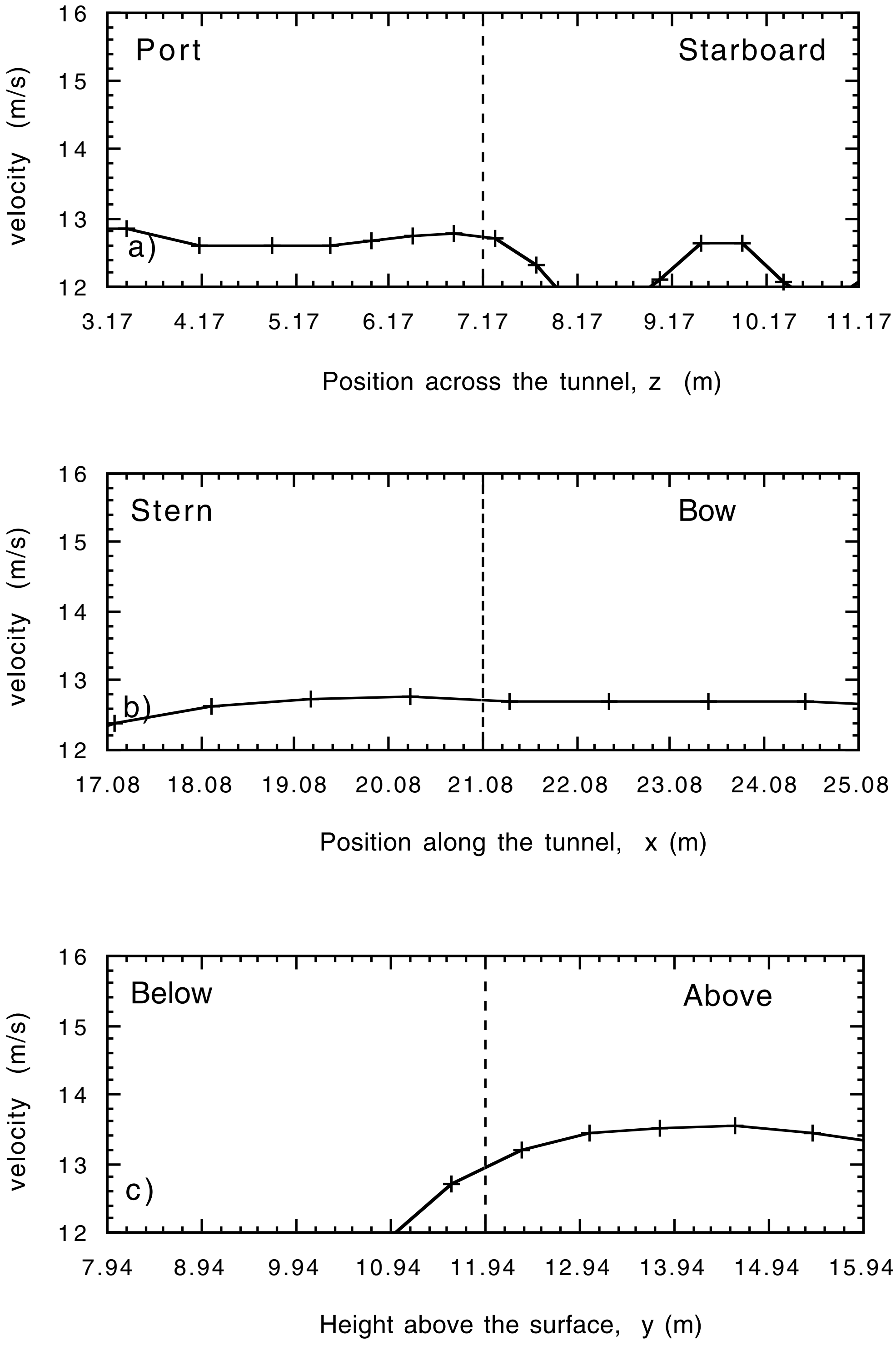
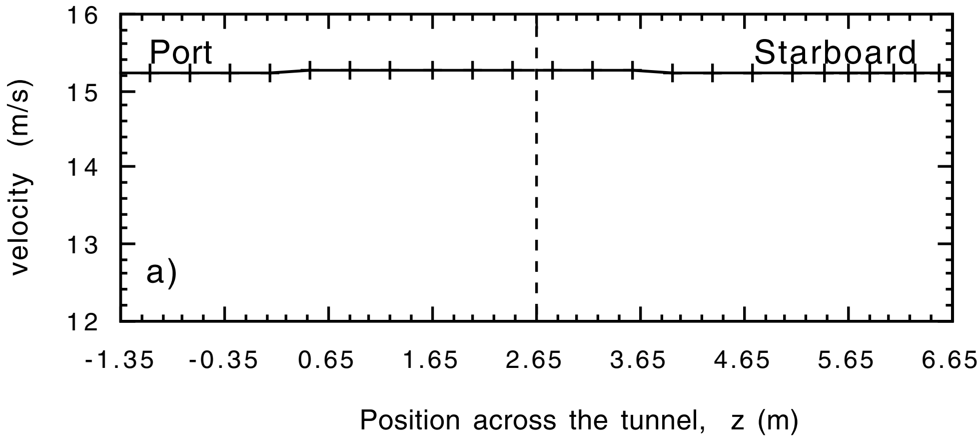
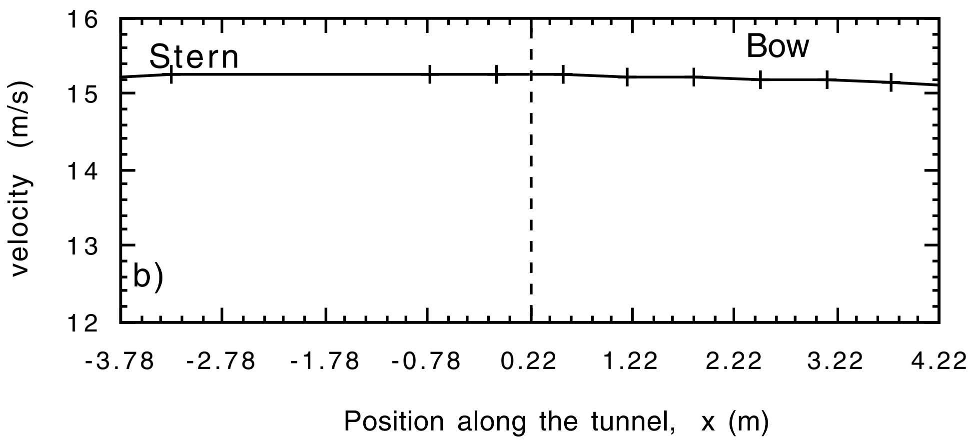


Figure 18 As Figure 15, but for the Vector E anemometer.





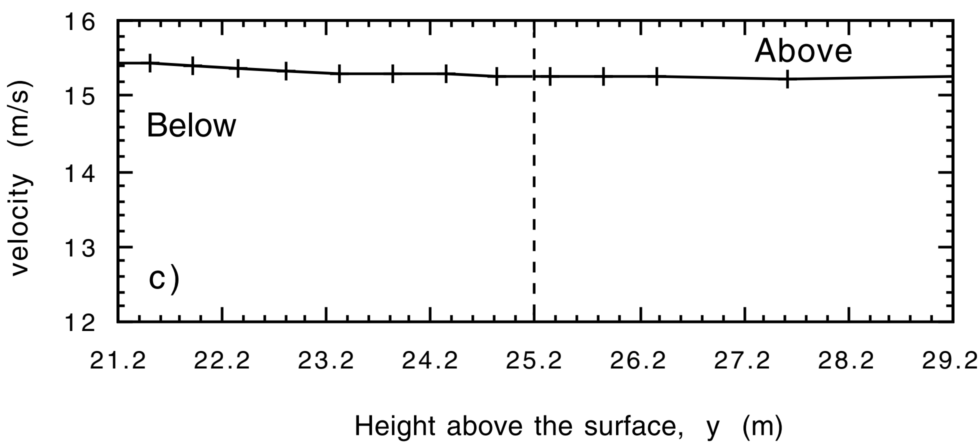


Figure 19 As Figure 12, but for the main mast research sonic anemometer.

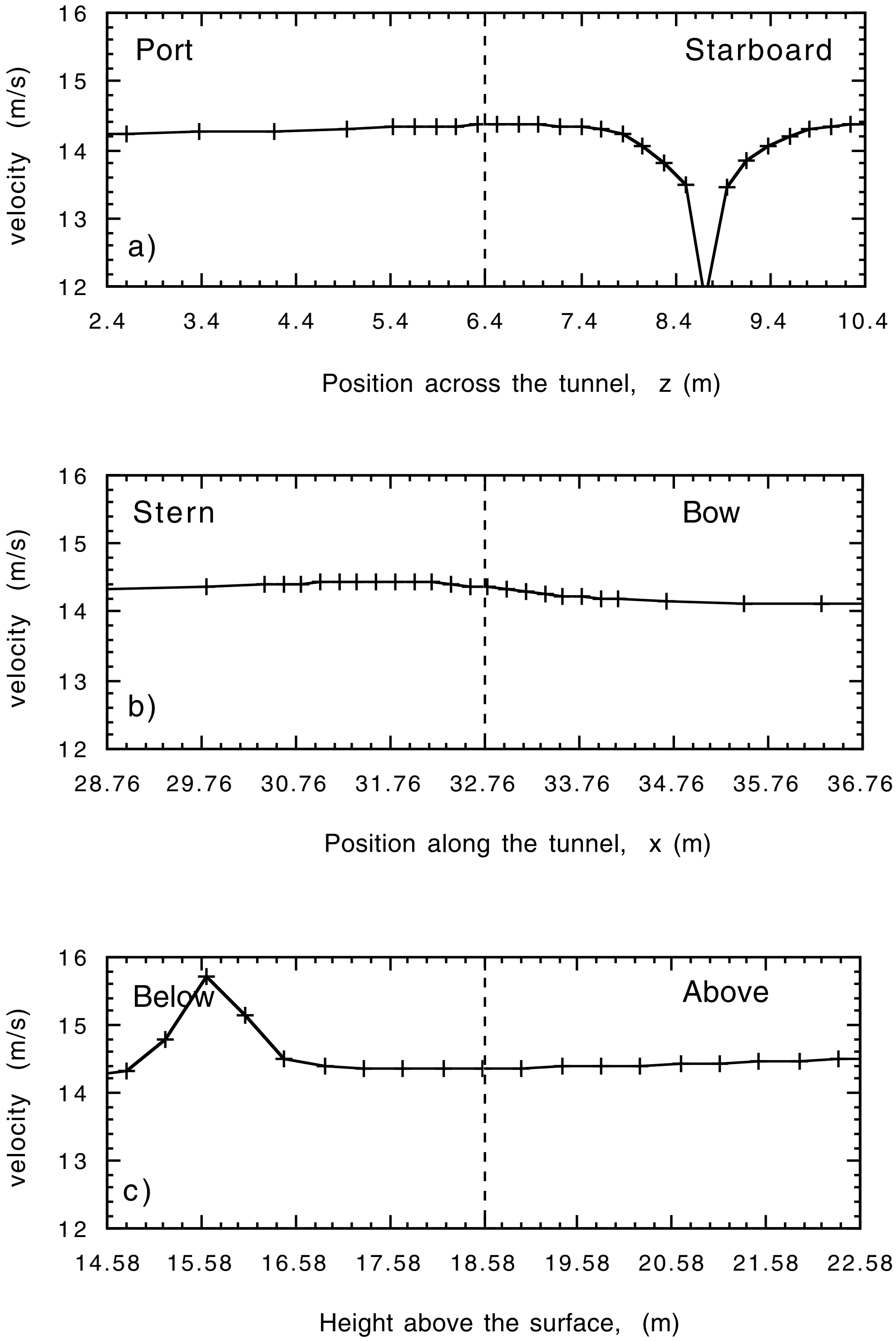


Figure 20 Lines of velocity data through the research sonic anemometer position (indicated by the dashed line) in all three directions; a) across the tunnel (z), b) along the tunnel (x) and c) vertically (y). Results are from a 15° flow over the starboard bow for cruises D223-D224.

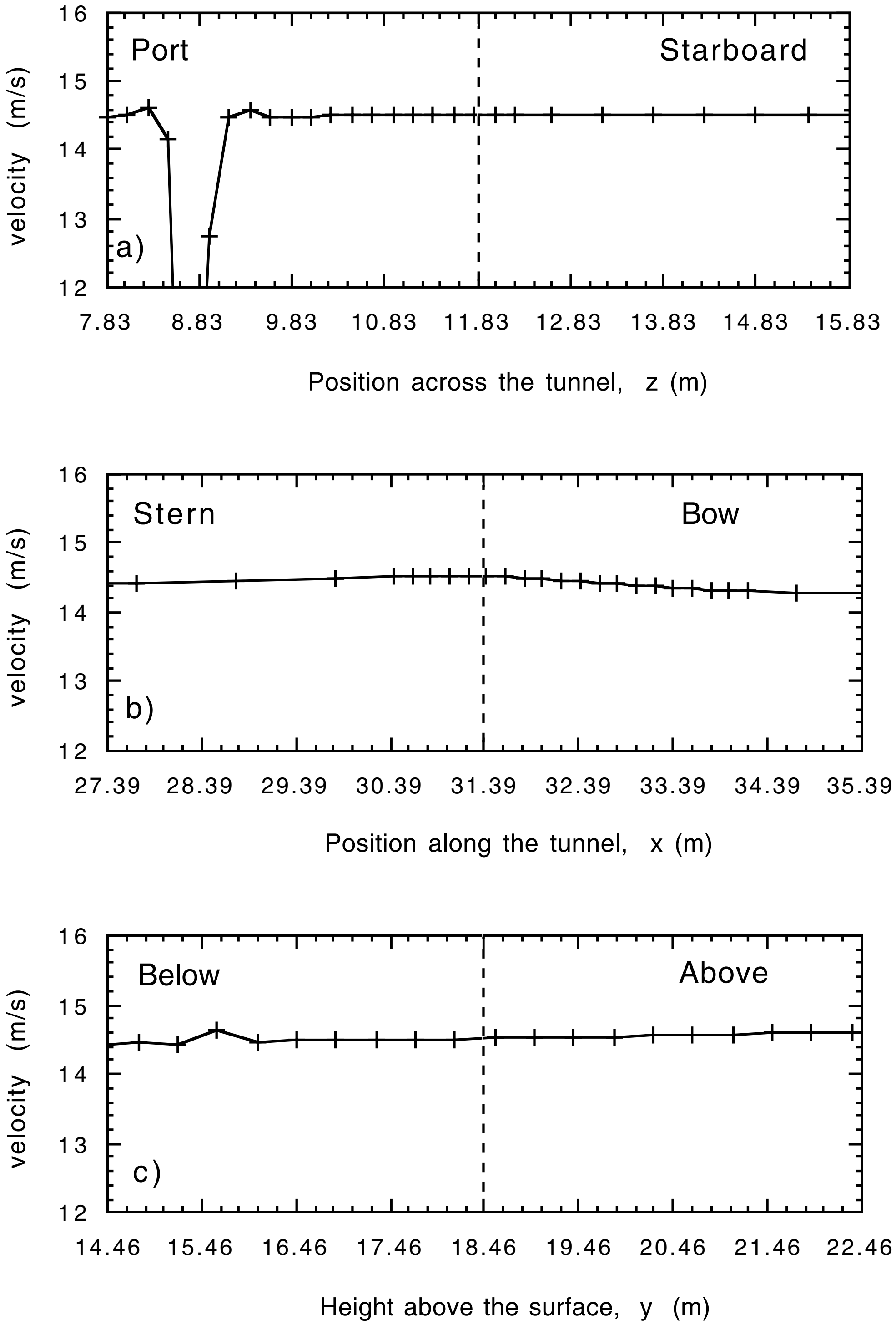


Figure 21 As Figure 20, but for the Wind Master sonic anemometer.

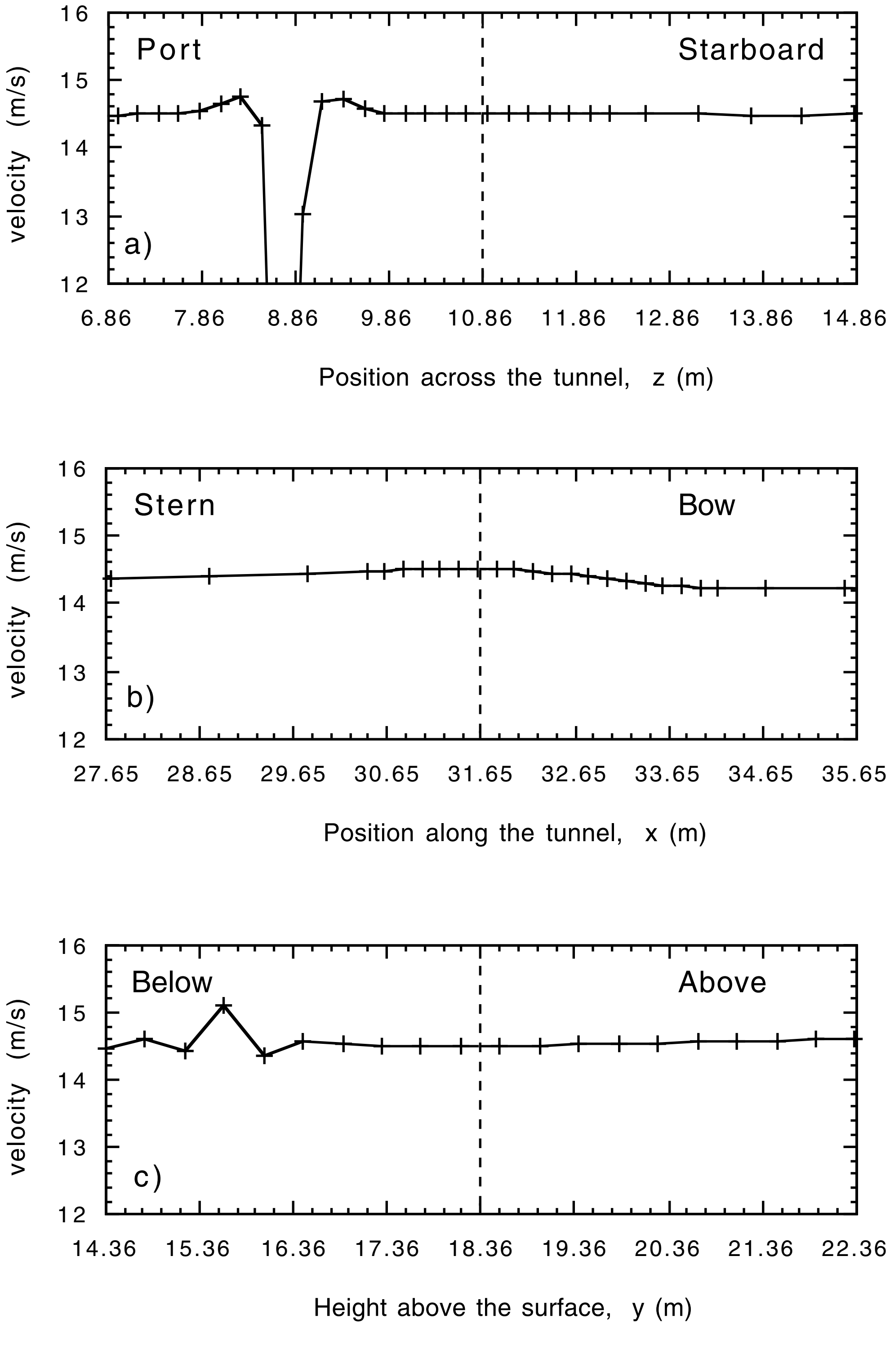


Figure 22 As Figure 20, but for the Young AQ. anemometer.

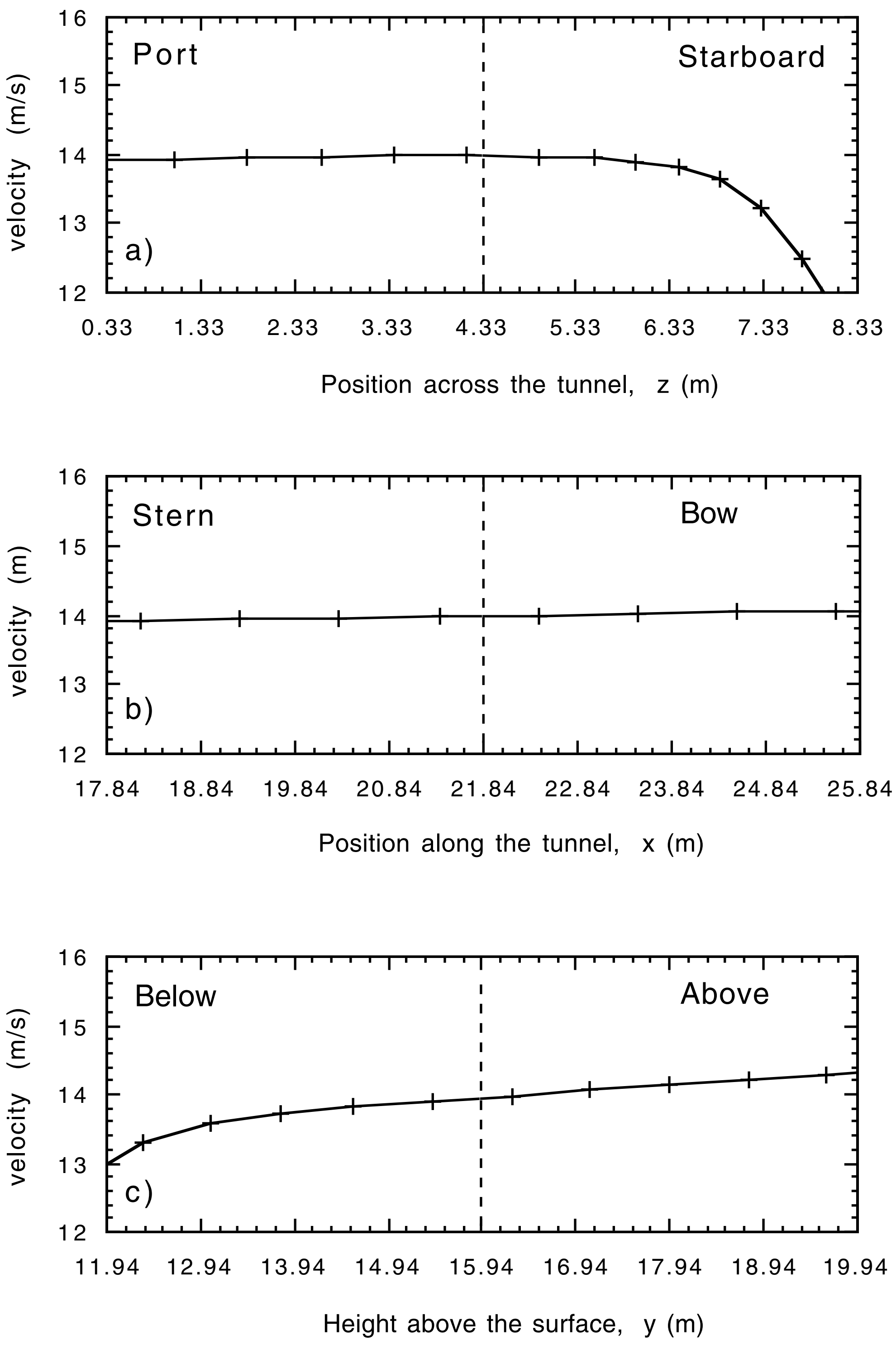


Figure 23 Lines of velocity data through the Vector A (highest) anemometer position (indicated by the dashed line) in all three directions; a) across the tunnel (z), b) along the tunnel (x) and c) vertically (y). Results are from a 15° flow over the starboard bow for cruise D223.

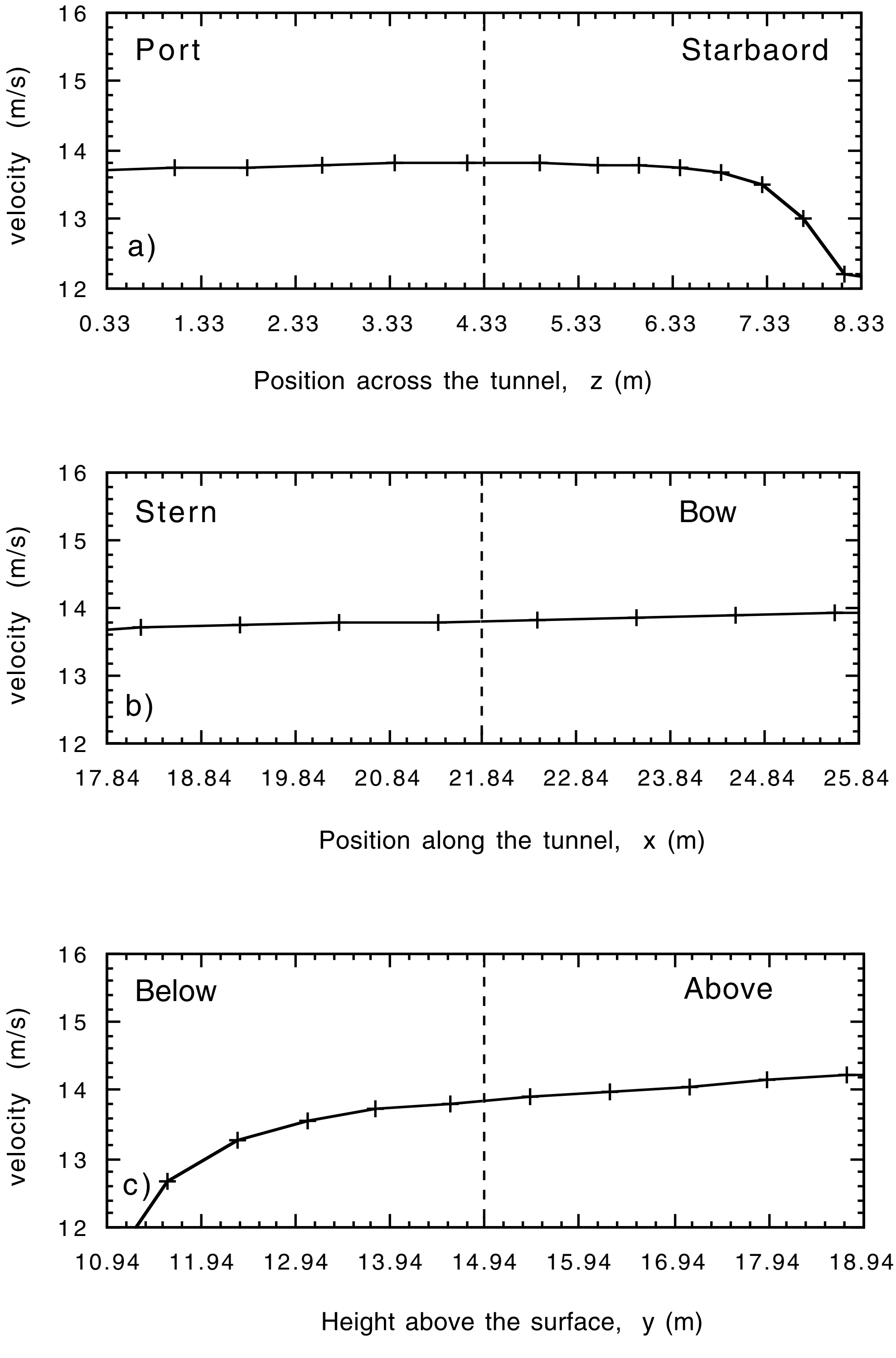
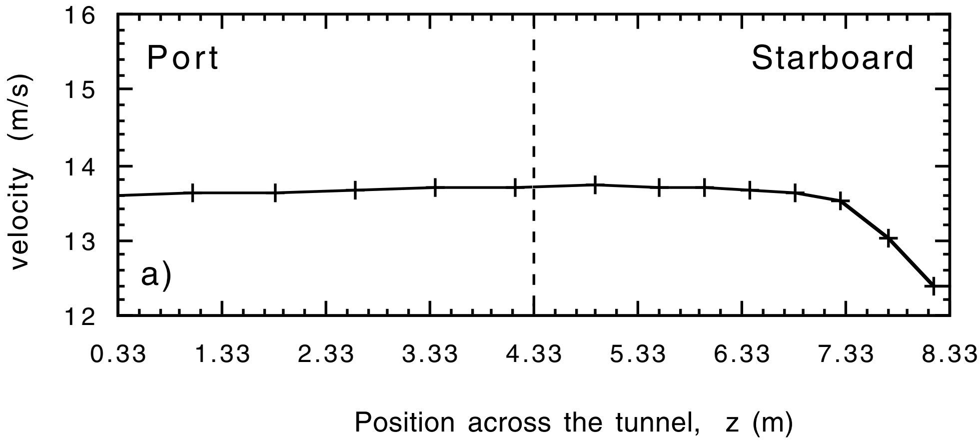
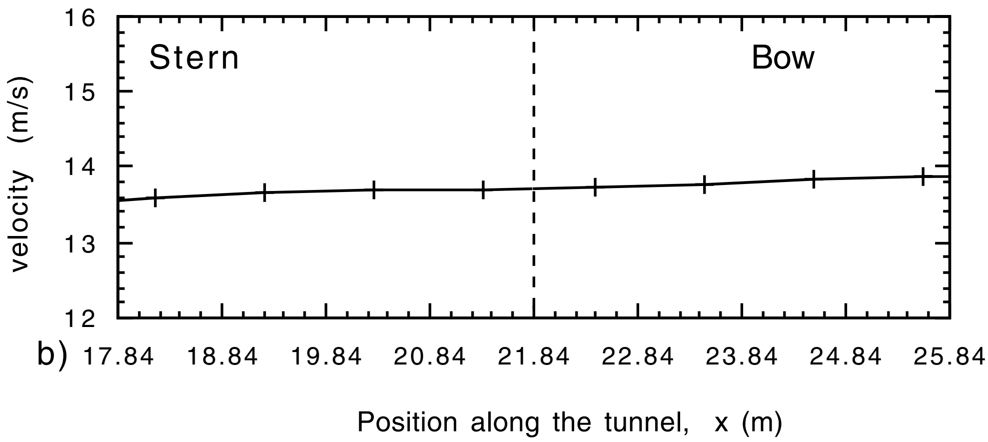


Figure 24 As Figure 23, but for the Vector B anemometer.





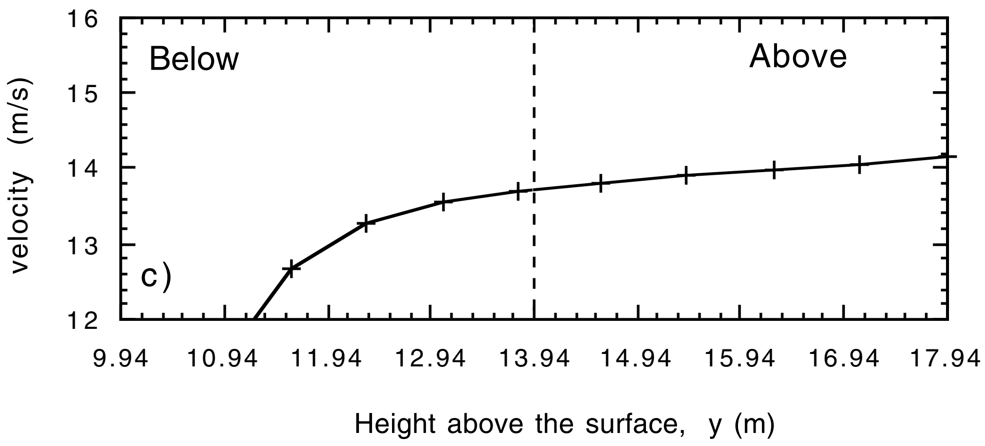


Figure 25 As Figure 23, but for the Vector C anemometer.

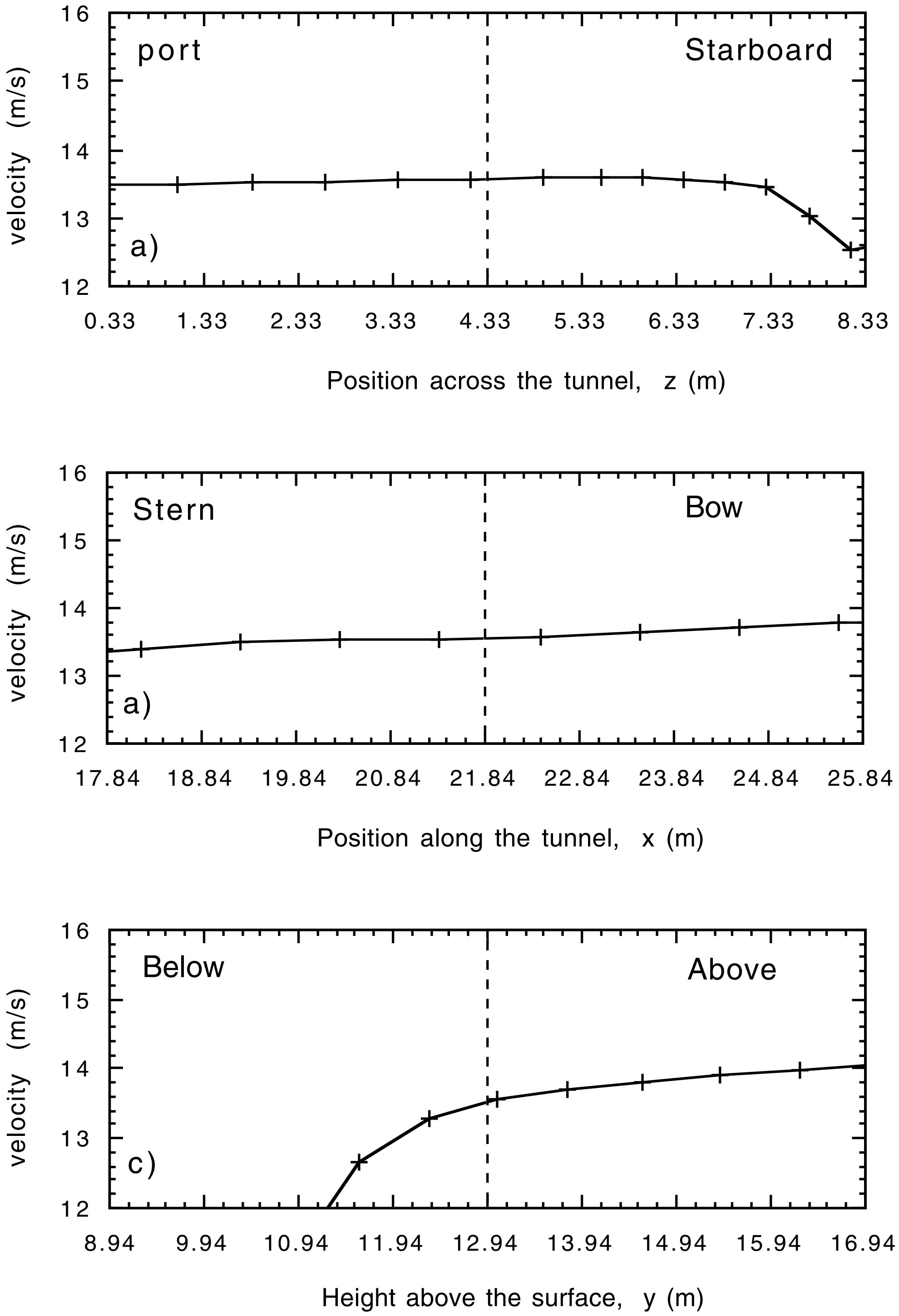


Figure 26 As Figure 23, but for the Vector D anemometer.

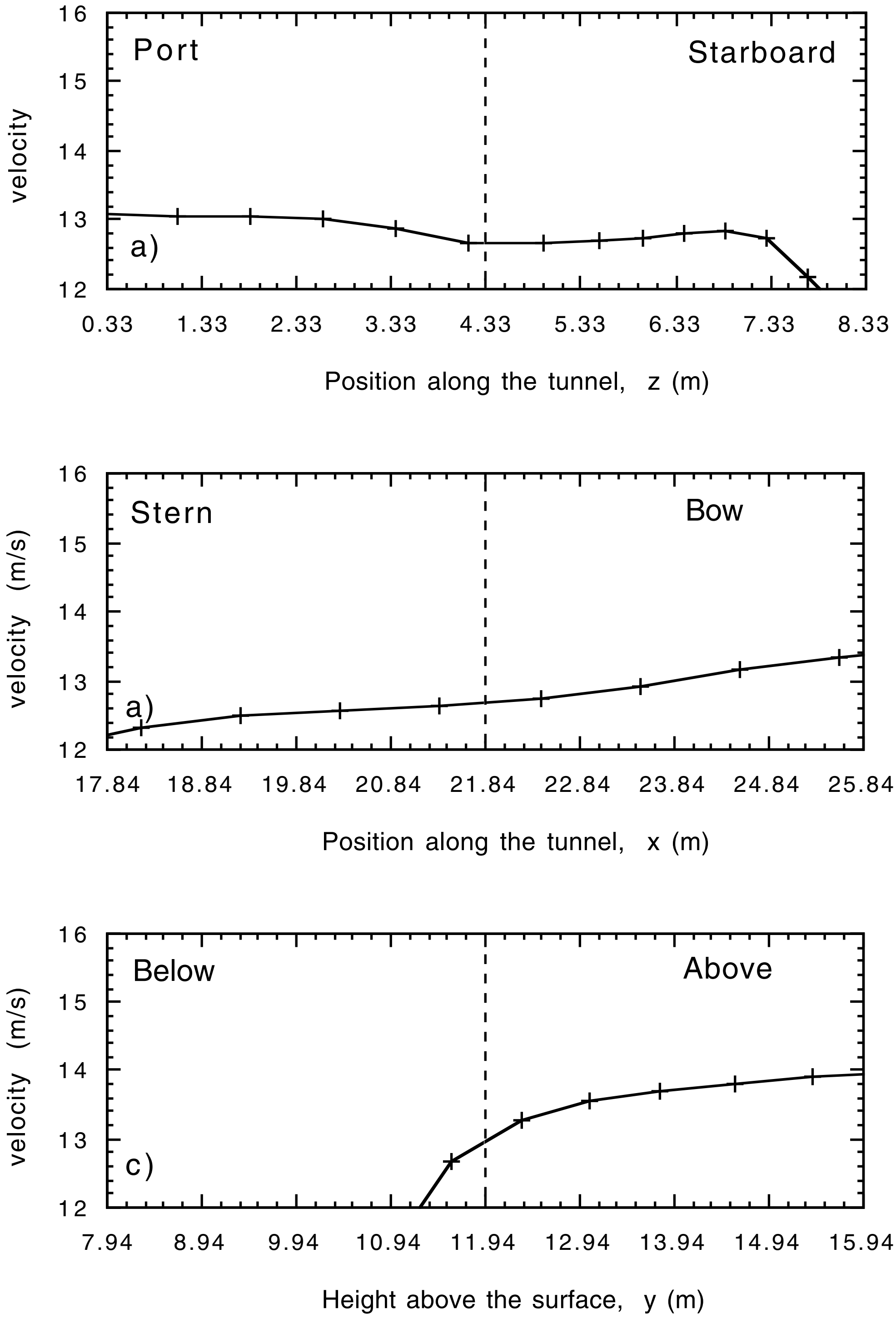


Figure 27 As Figure 23, but for the Vector E anemometer.

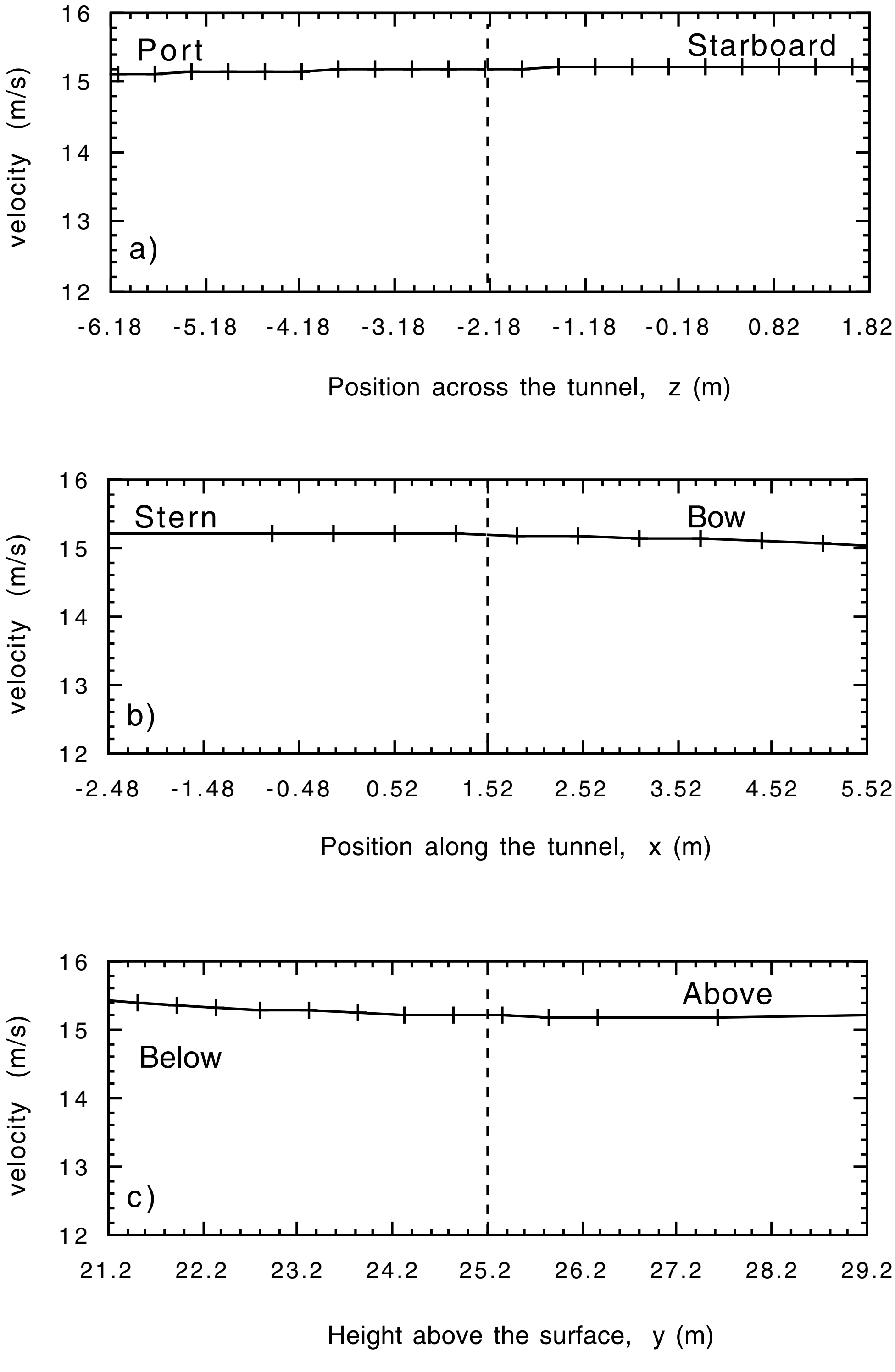


Figure 28 As Figure 20, but for the main mast research sonic.

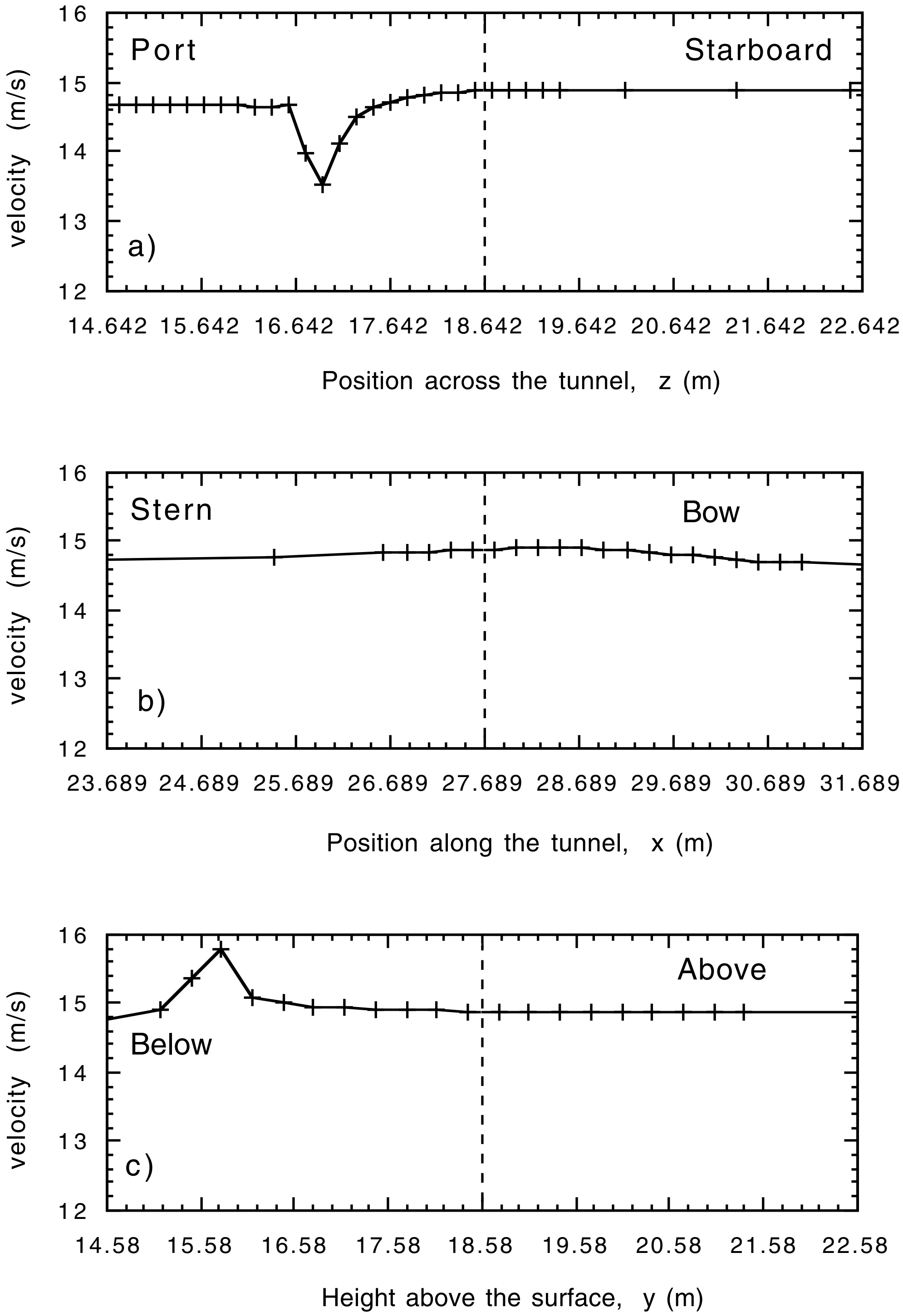


Figure 29 Lines of velocity data through the research sonic anemometer position (indicated by the dashed line) in all three directions; a) across the tunnel (z), b) along the tunnel (x) and c) vertically (y). Results are from a 30° flow over the port bow for cruises D223-D224.

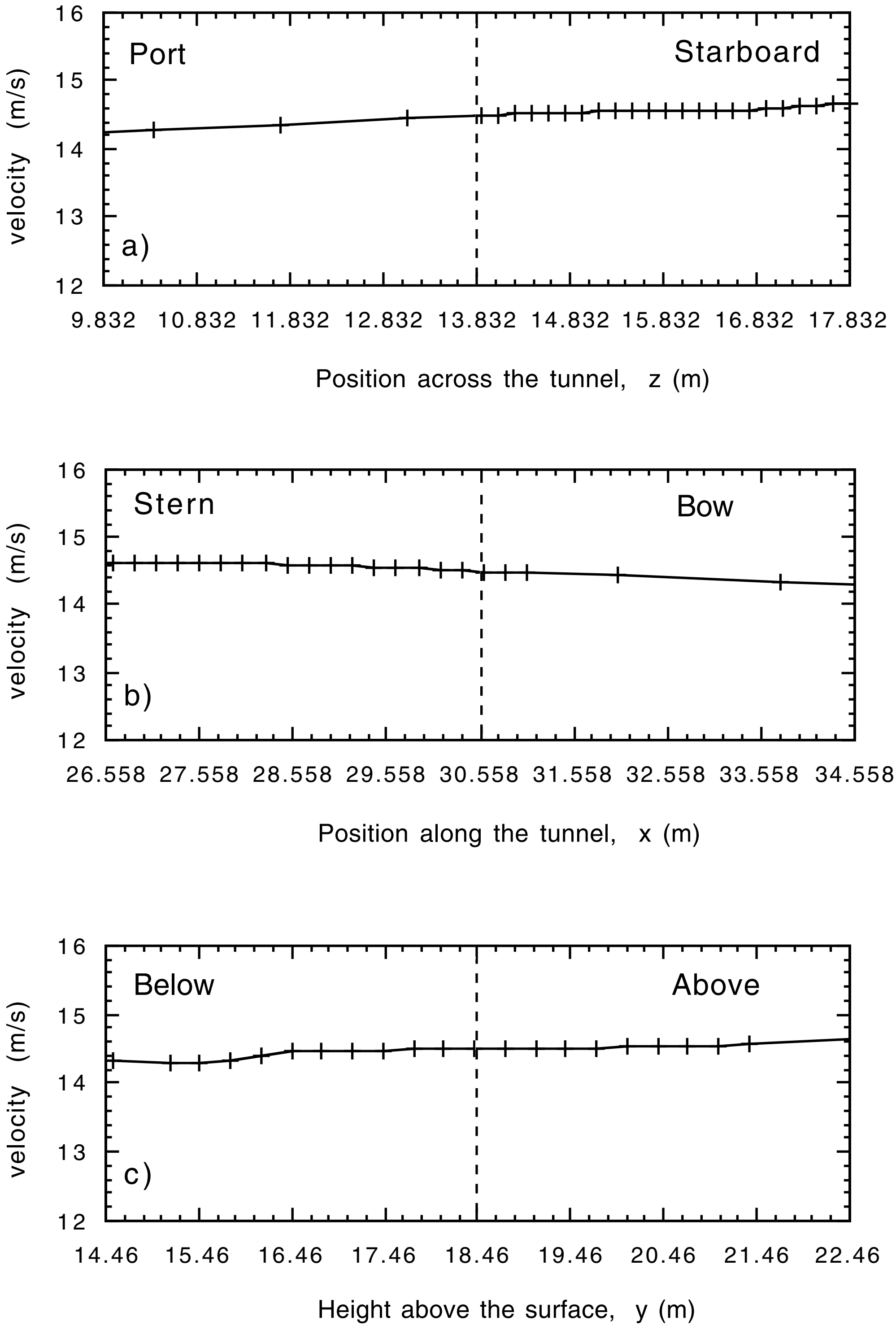


Figure 30 As Figure 29, but for the Wind Master sonic anemometer.

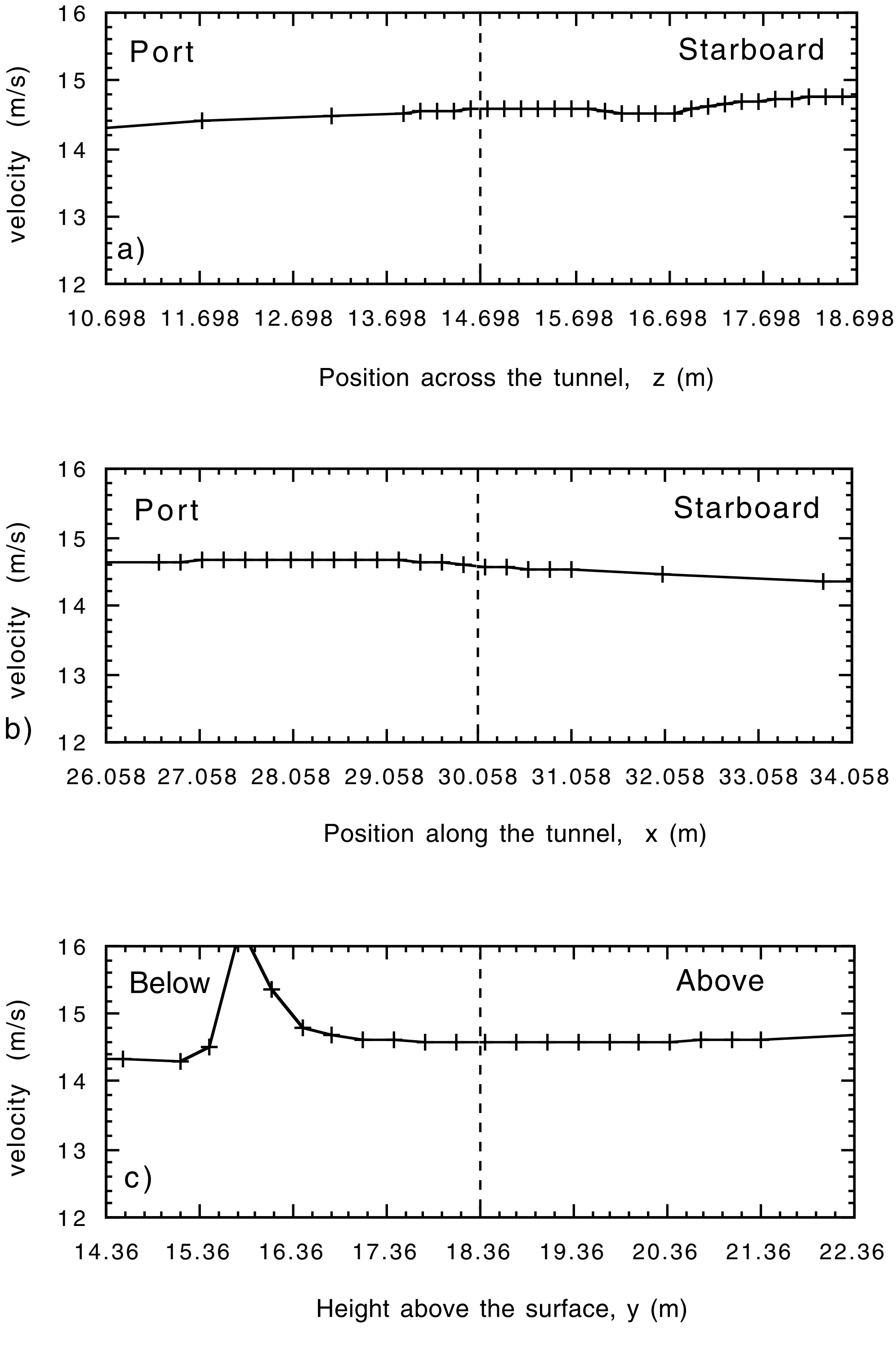


Figure 31 As Figure 29, but for the Young AQ anemometer.

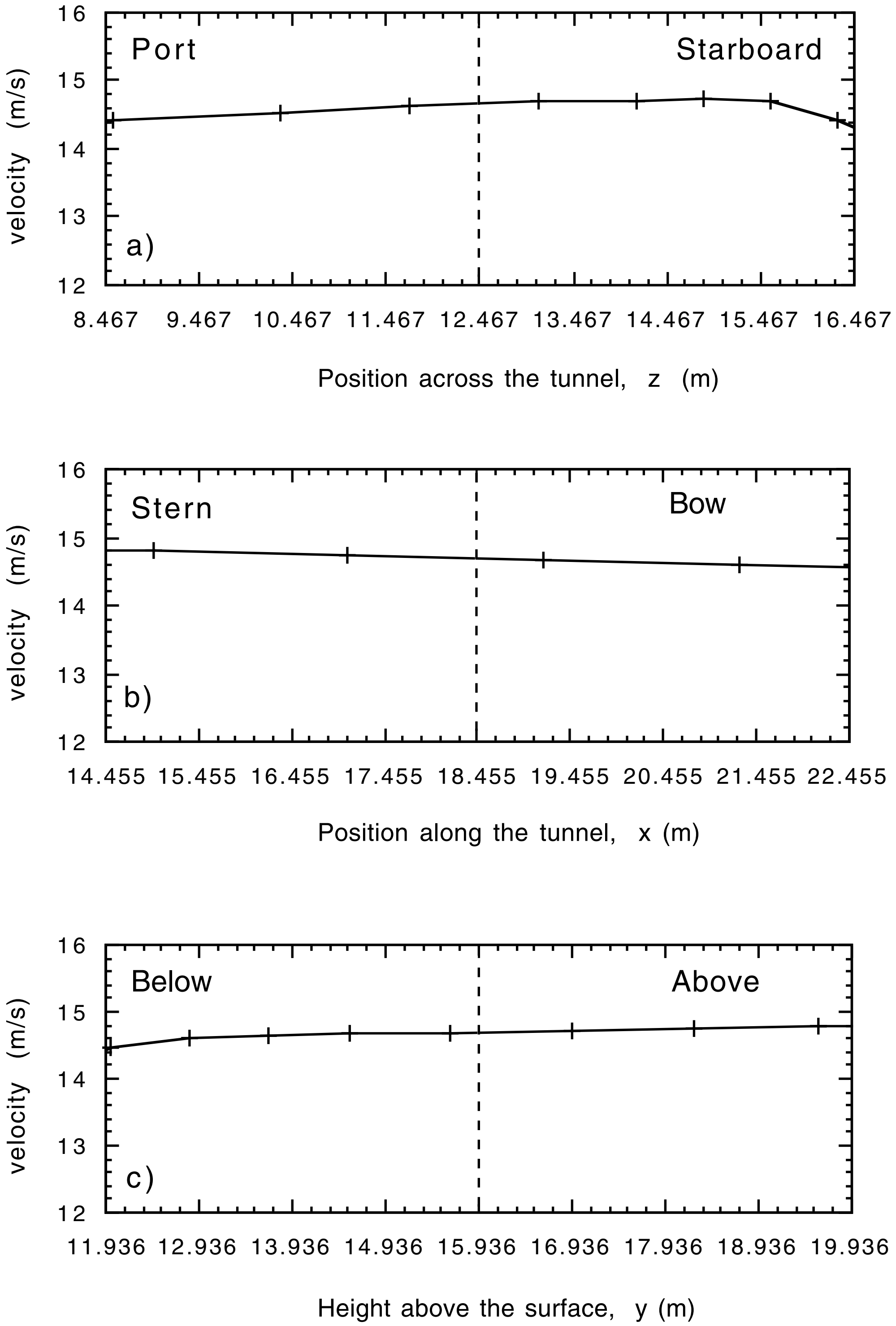


Figure 32 Lines of velocity data through the Vector A (highest) anemometer position (indicated by the dashed line) in all three directions; a) across the tunnel (z), b) along the tunnel (x) and c) vertically (y). Results are from a 30° flow over the port bow for cruise D223.

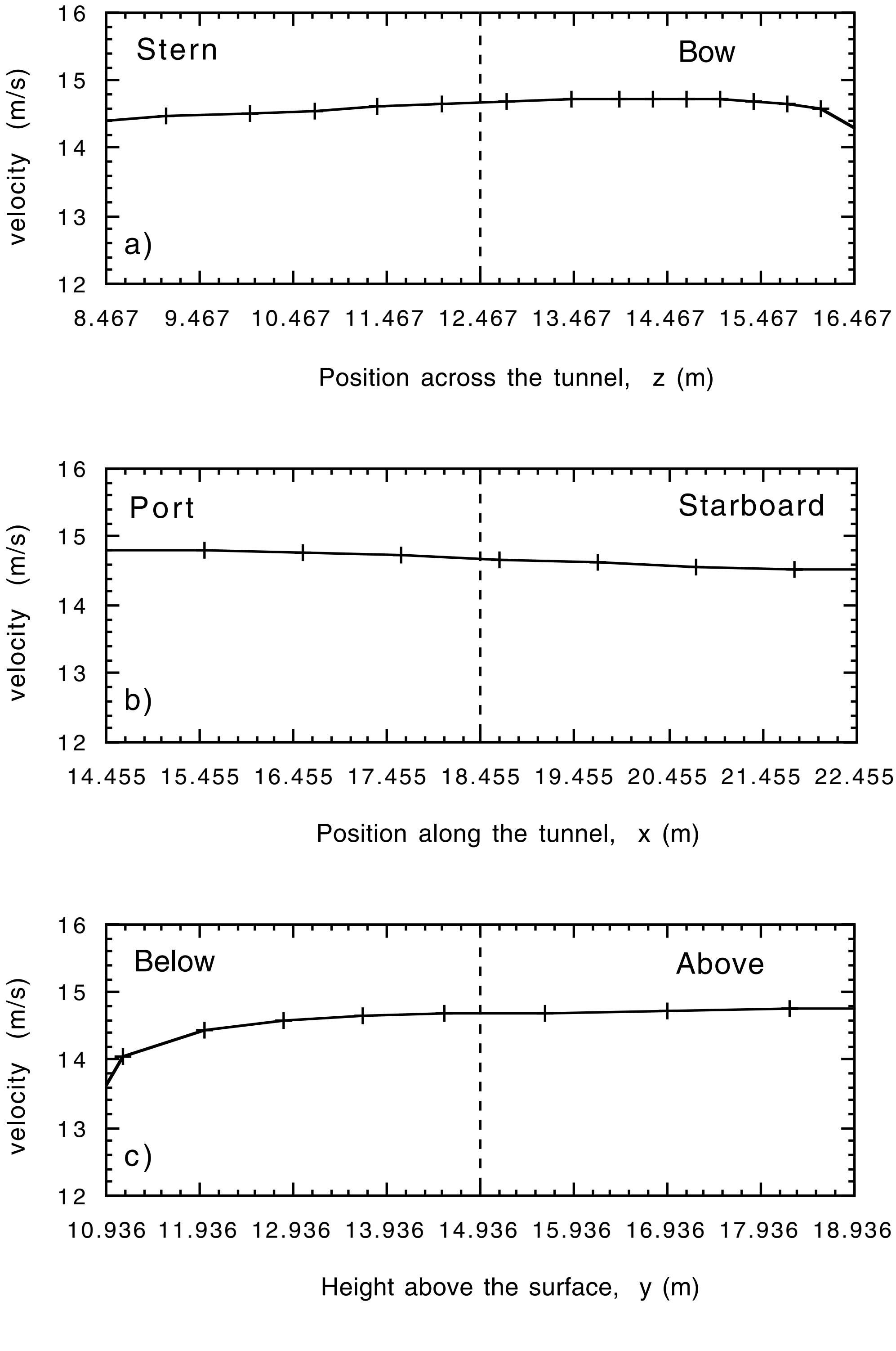


Figure 33 As Figure 32, but for the Vector B anemometer.

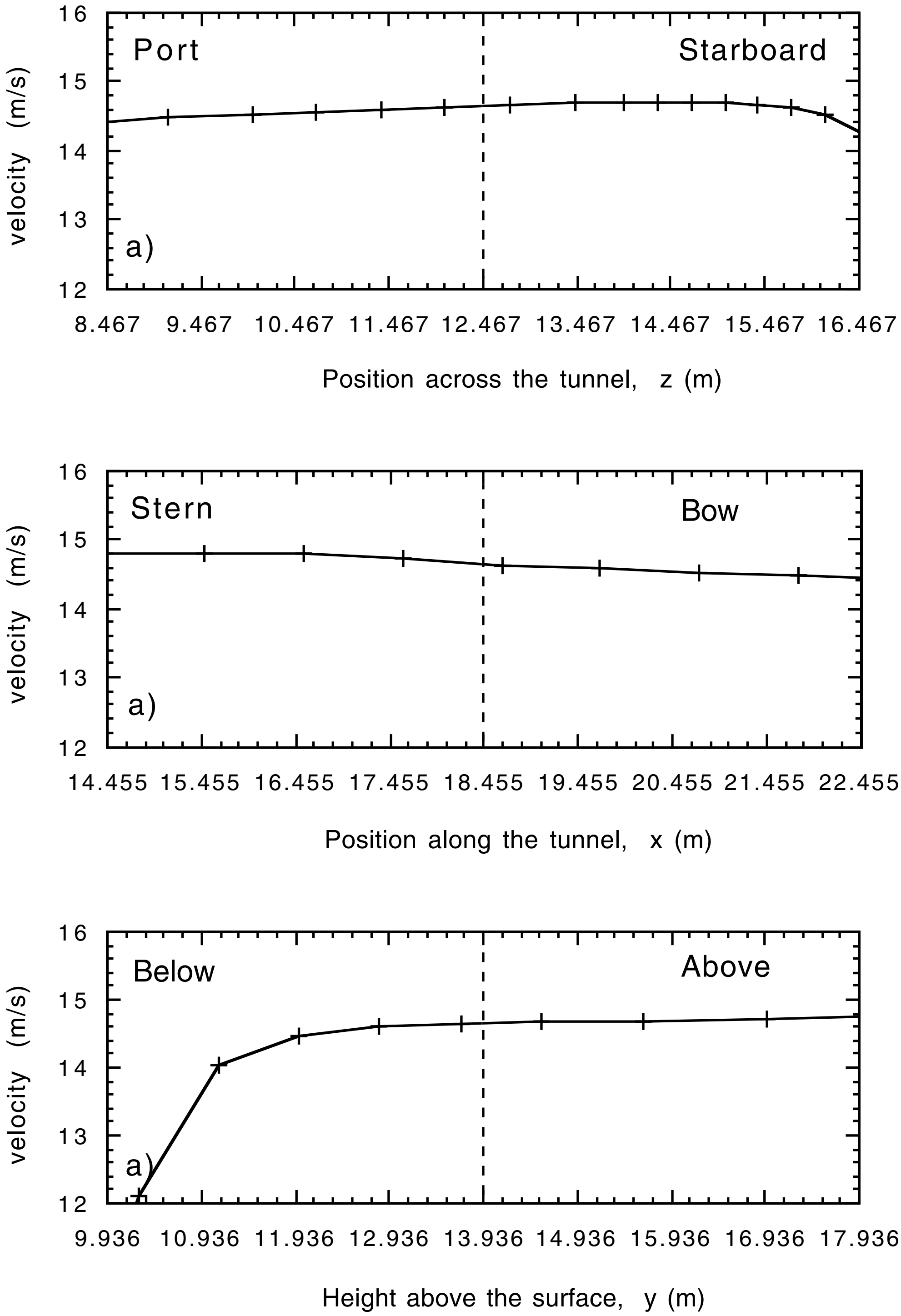


Figure 34 As Figure 32, but for the Vector C anemometer.

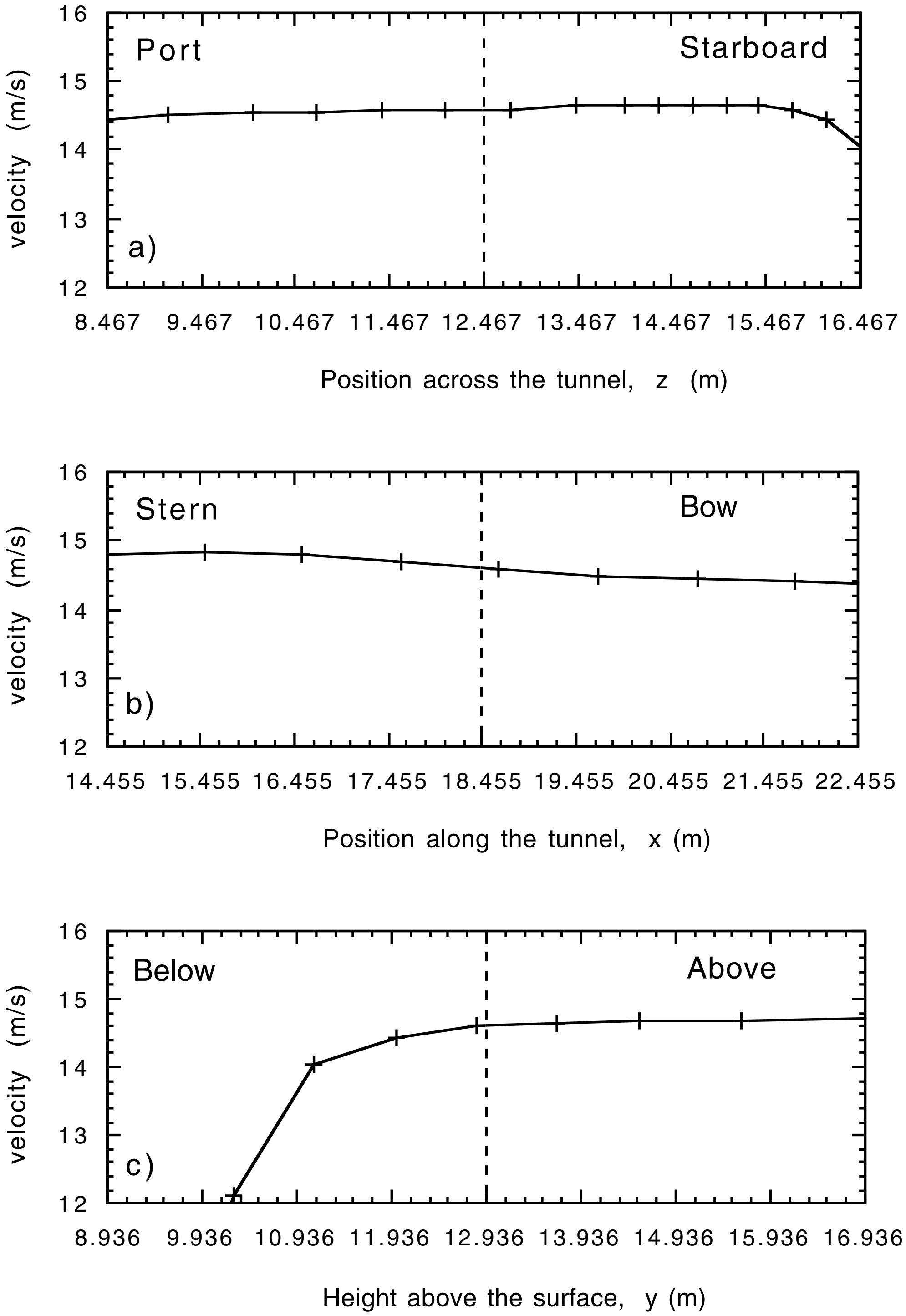


Figure 35 As Figure 32, but for the Vector D anemometer.

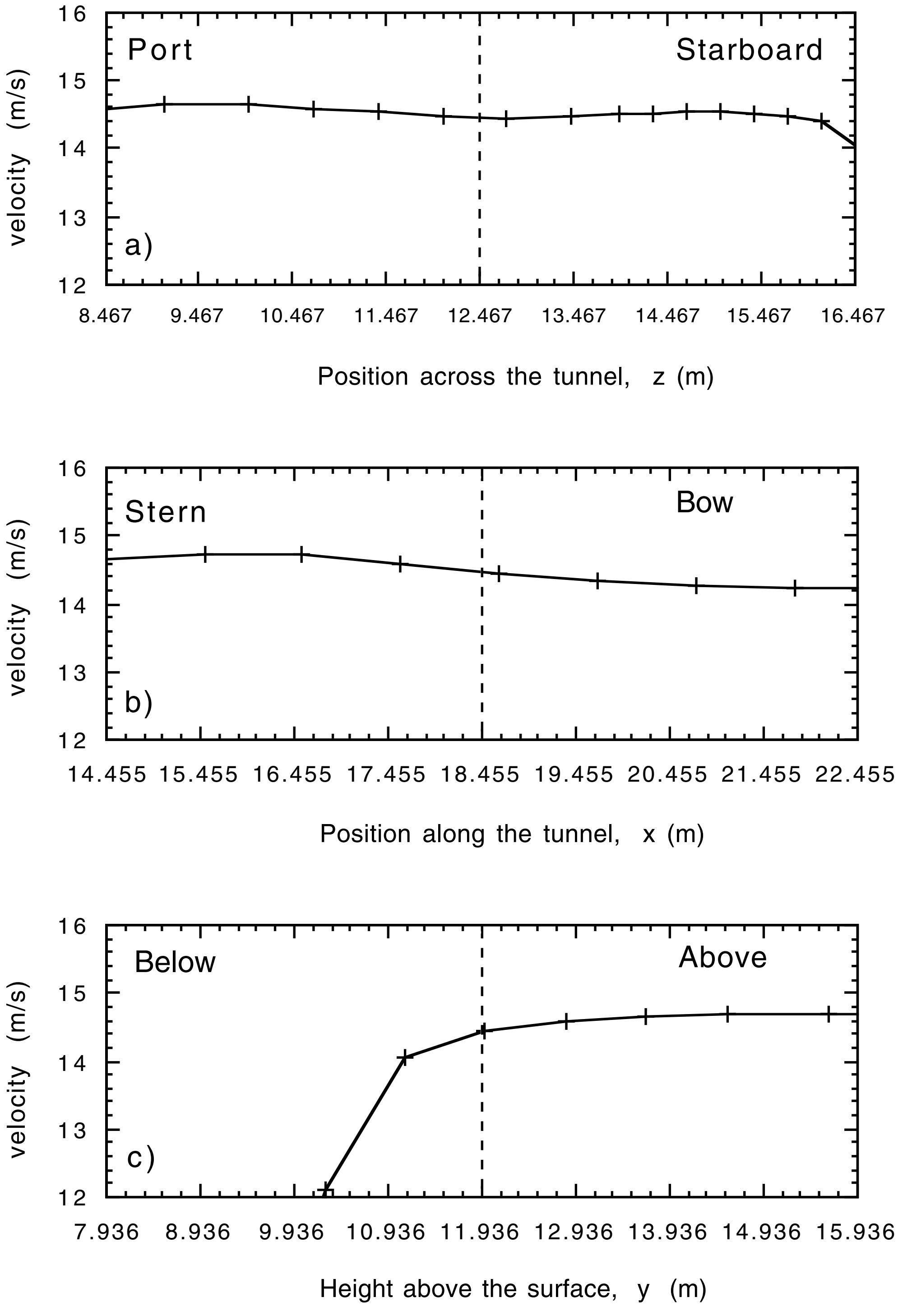


Figure 36 As Figure 32, but for the Vector E (lowest) anemometer.

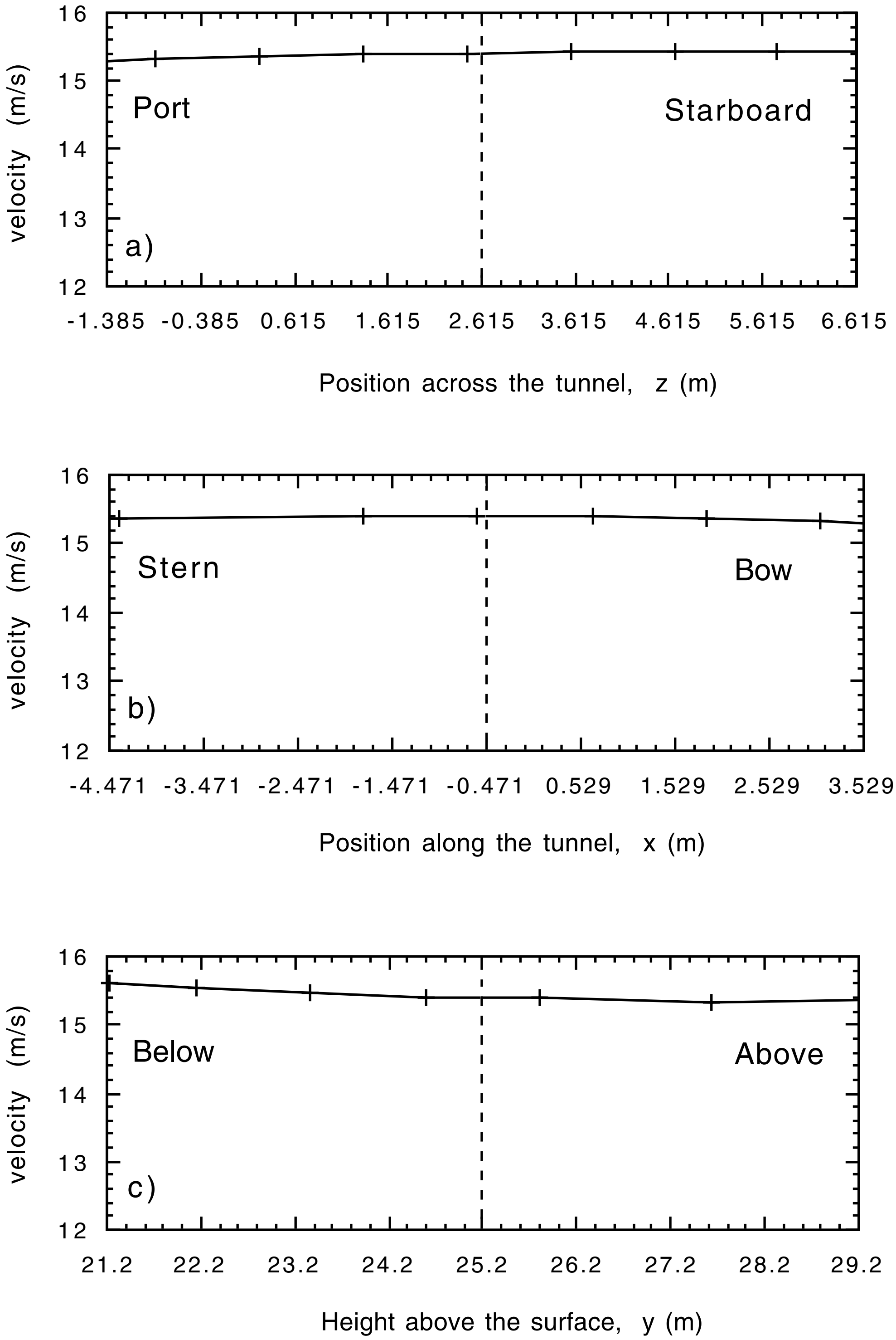


Figure 37 As Figure 29, but for the main mast research sonic anemometer.

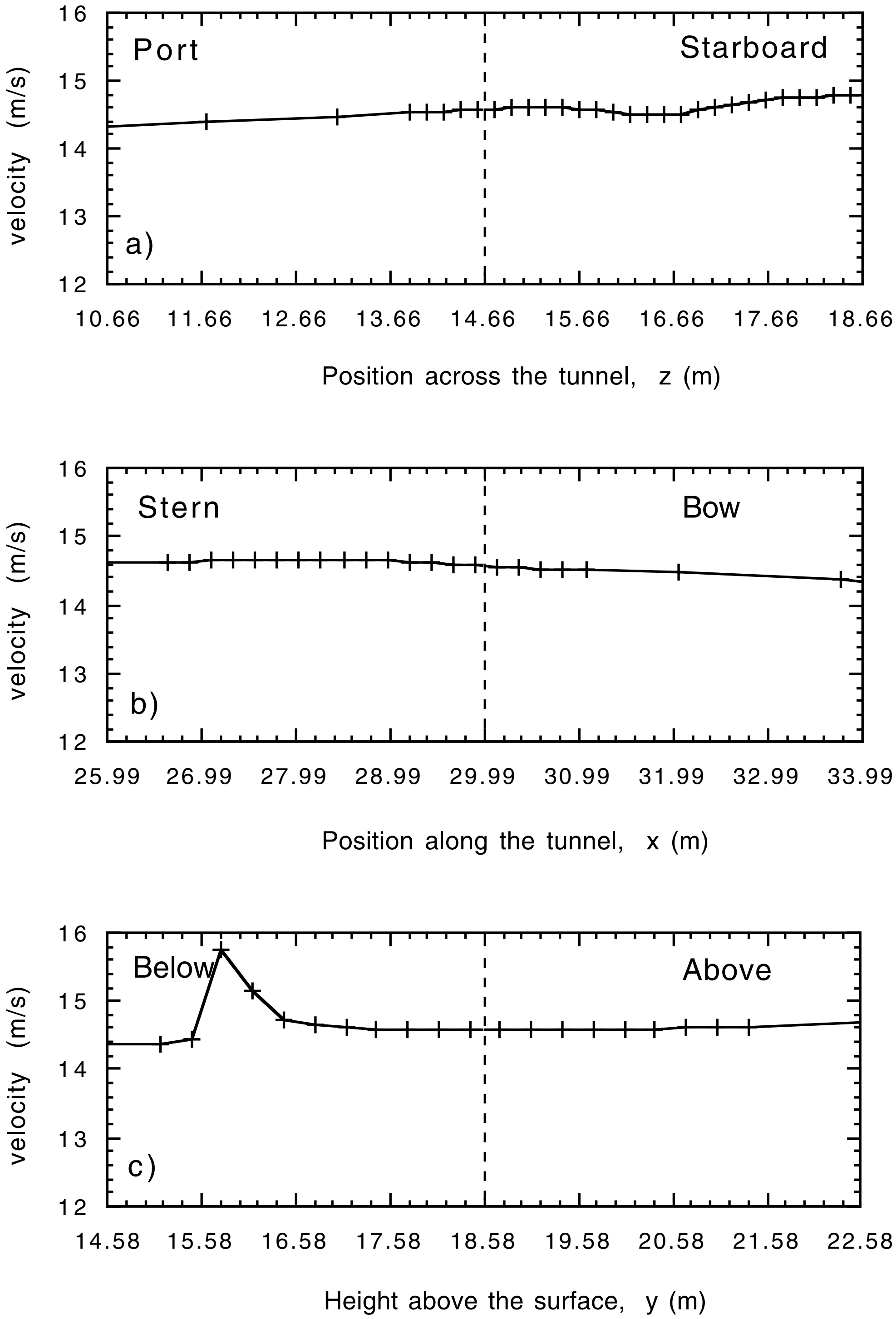


Figure 38 Lines of velocity data through the research sonic anemometer position (indicated by the dashed line) in all three directions; a) across the tunnel (z), b) along the tunnel (x) and c) vertically (y). Results are from a 30° flow over the starboard bow for cruises D223-D224.

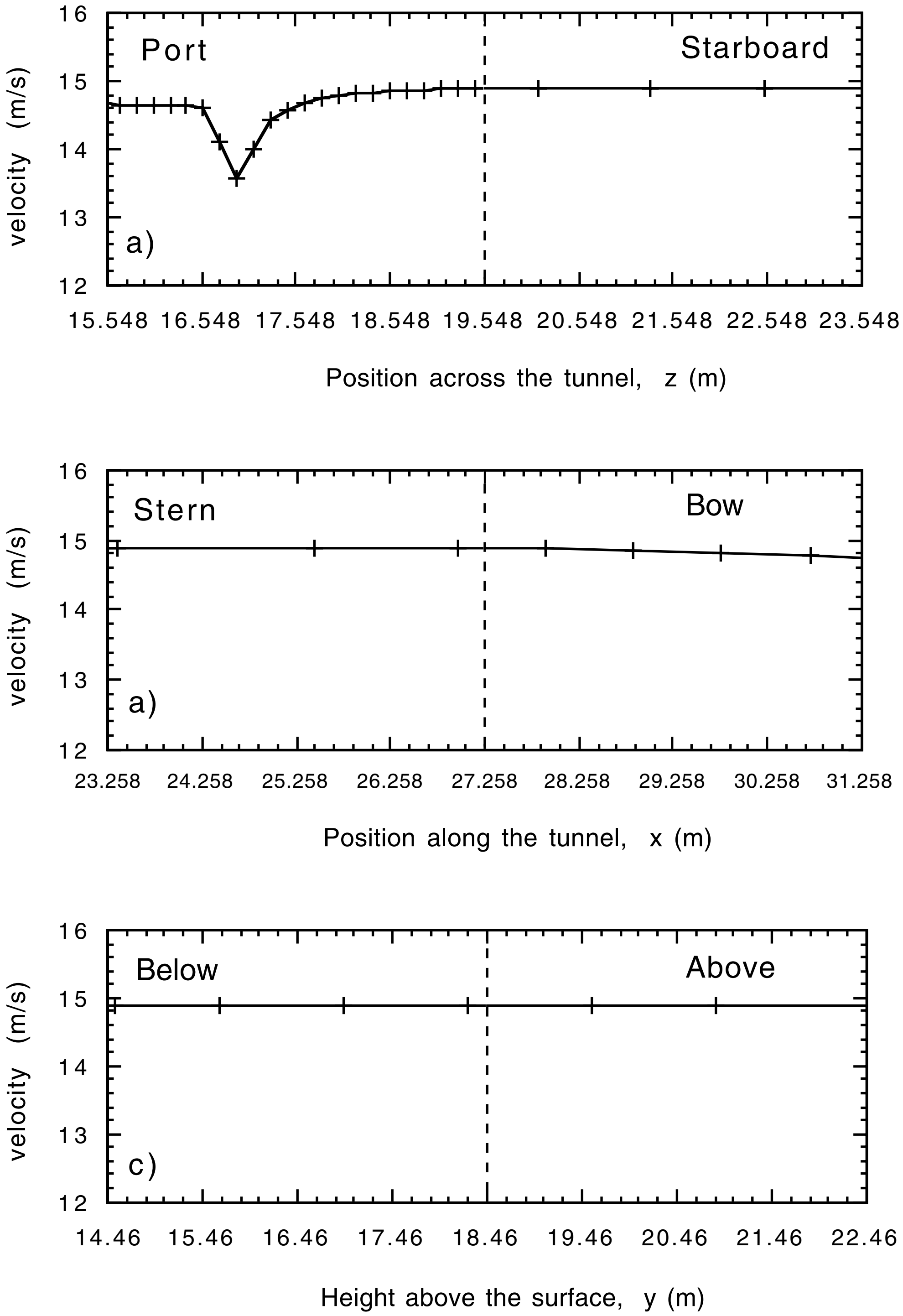


Figure 39 As Figure 38, but for the Wind Master sonic anemometer.

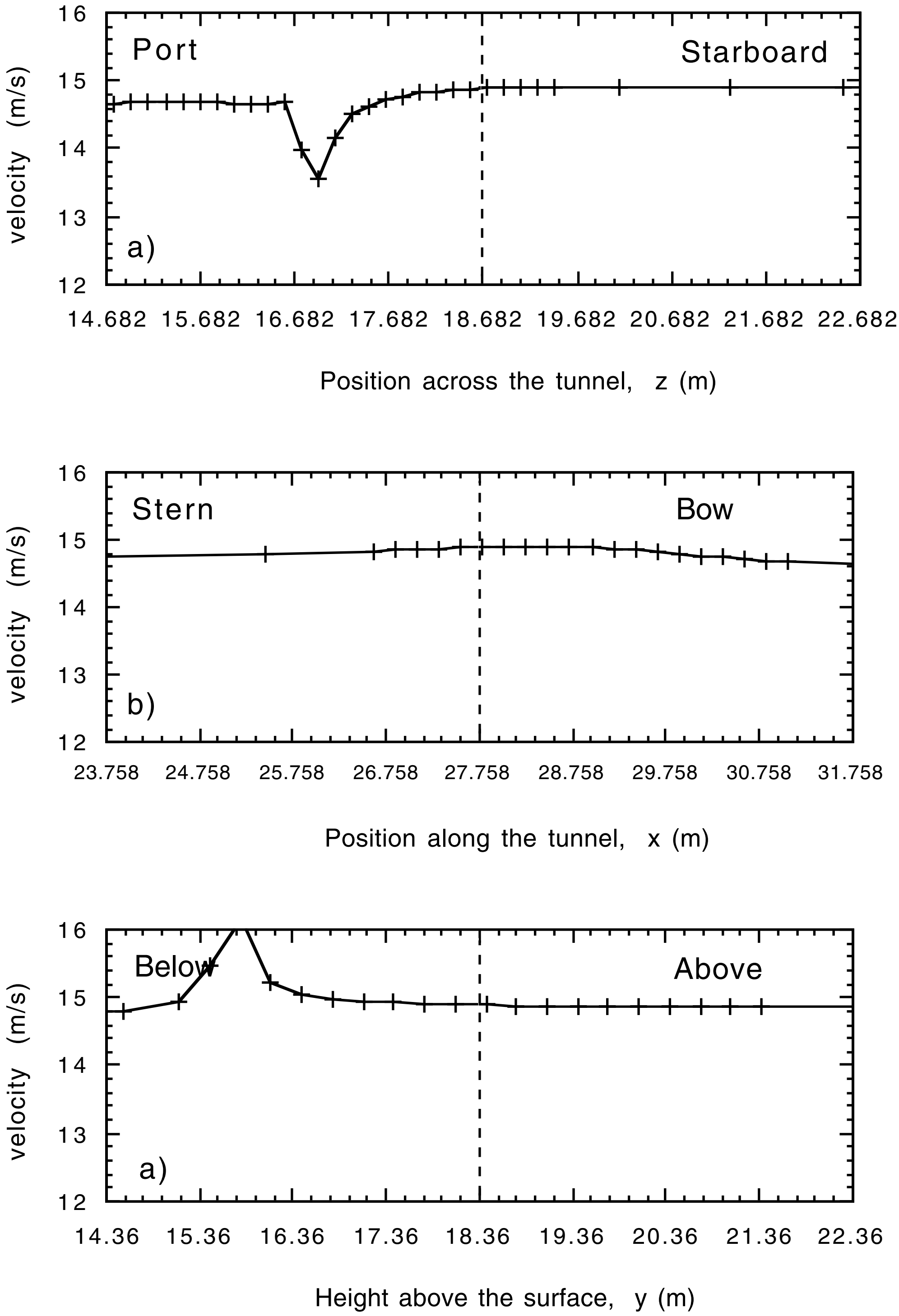


Figure 40 As Figure 38, but for the Young AQ anemometer.

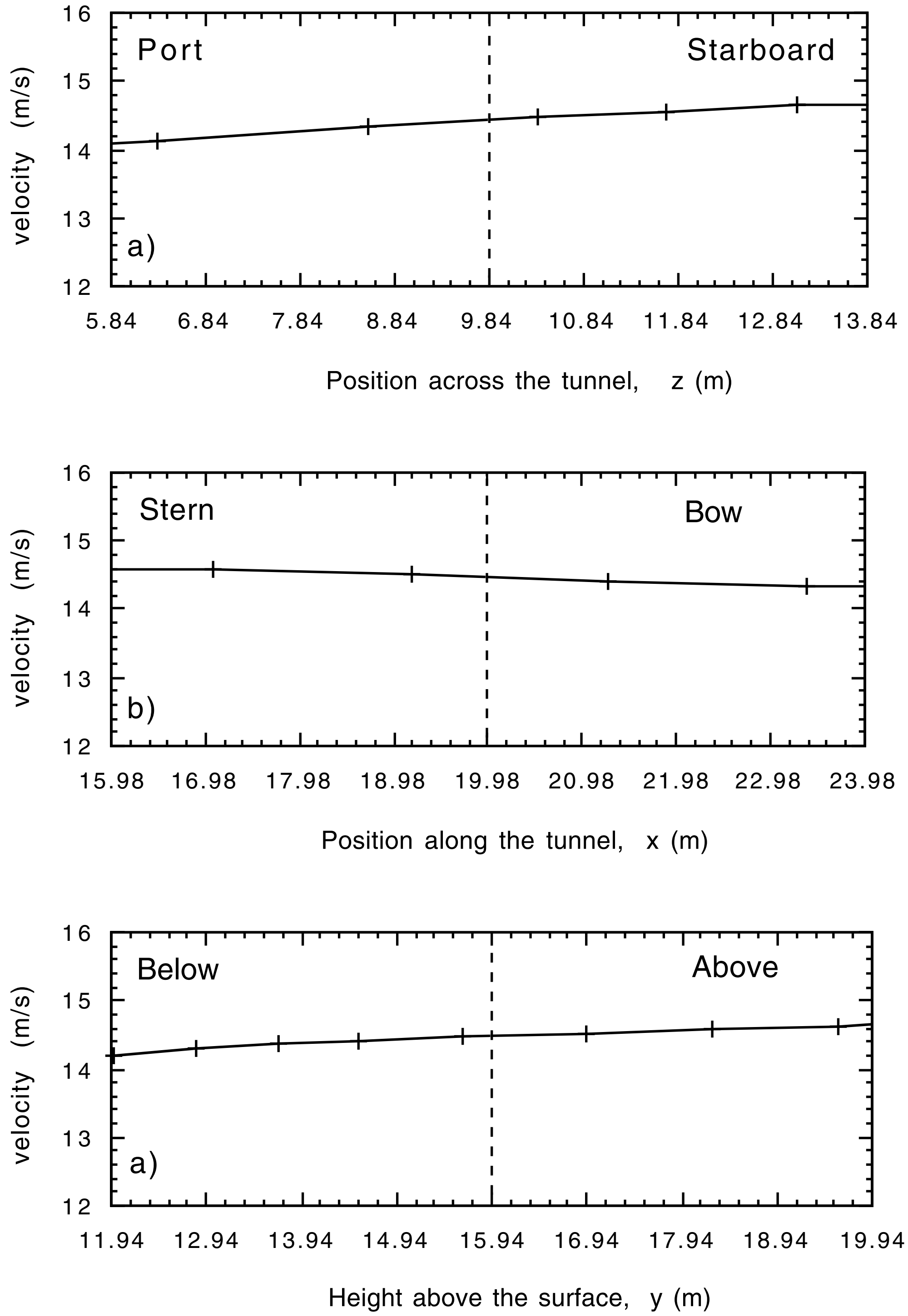


Figure 41 Lines of velocity data through the Vector A (highest) anemometer position (indicated by the dashed line) in all three directions; a) across the tunnel (z), b) along the tunnel (x) and c) vertically (y). Results are from a 30° flow over the starboard bow for cruise D223.

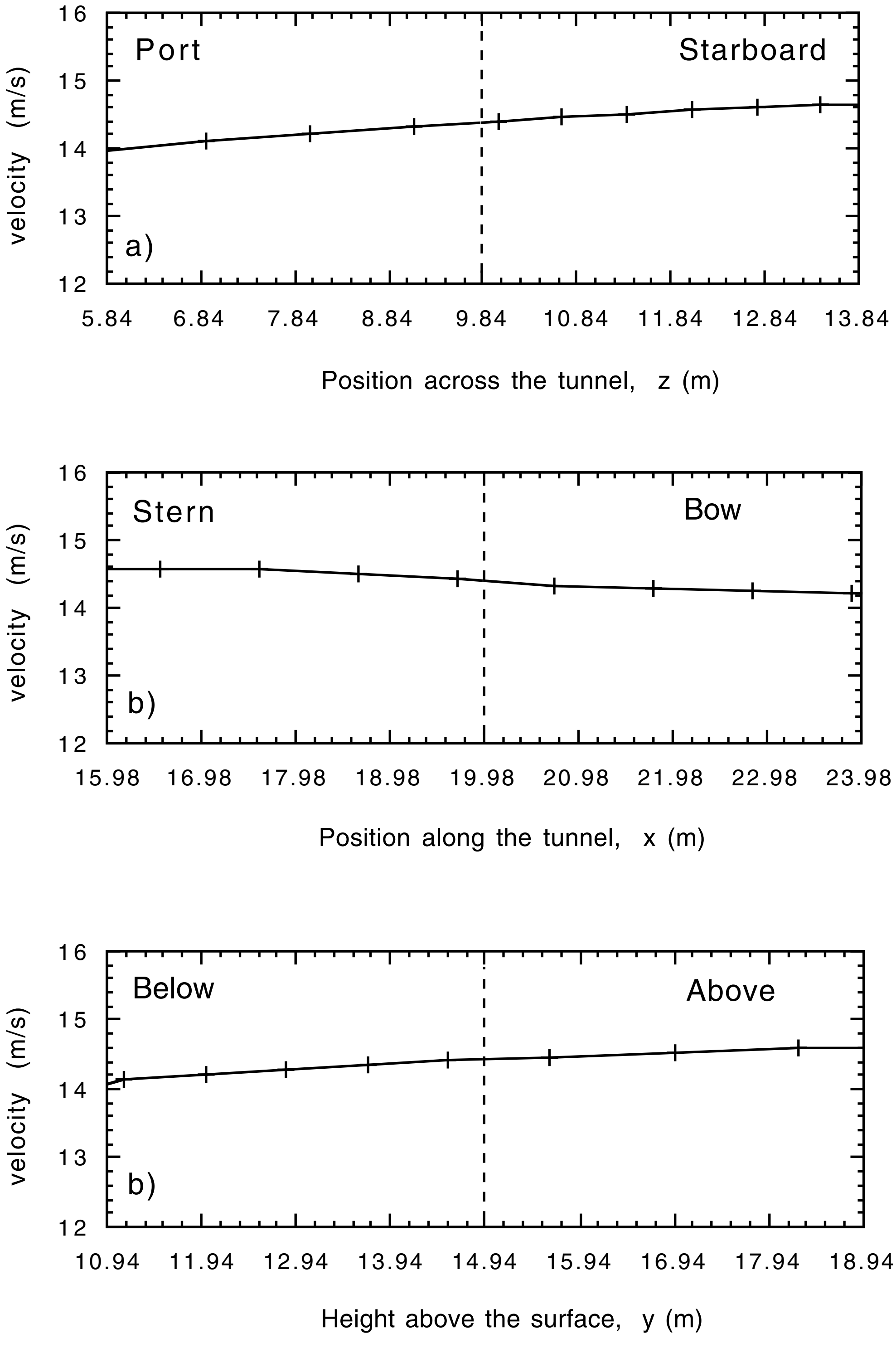


Figure 42 As Figure 41, but for the Vector B anemometer.

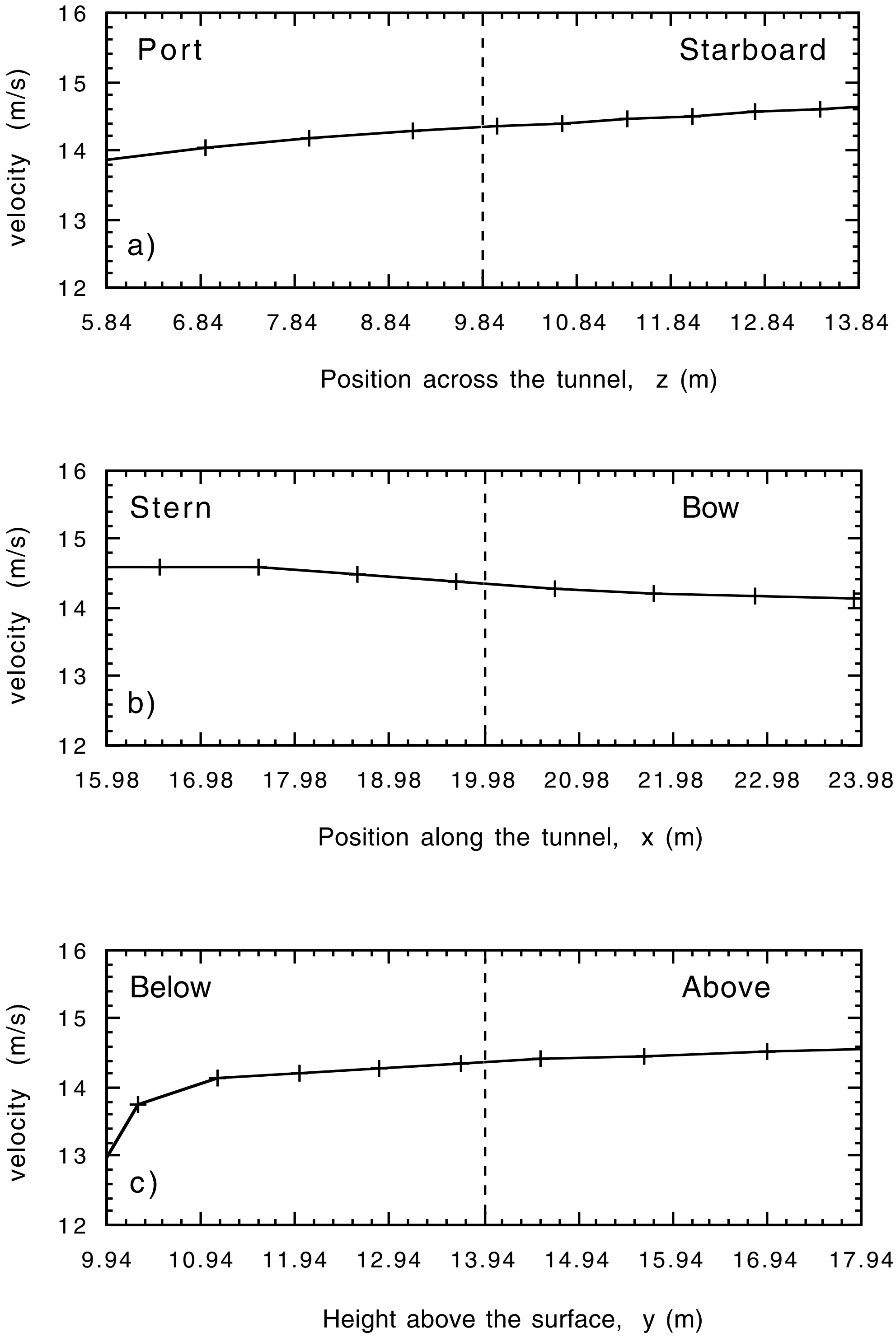


Figure 43 As Figure 41, but for the Vector C anemometer.

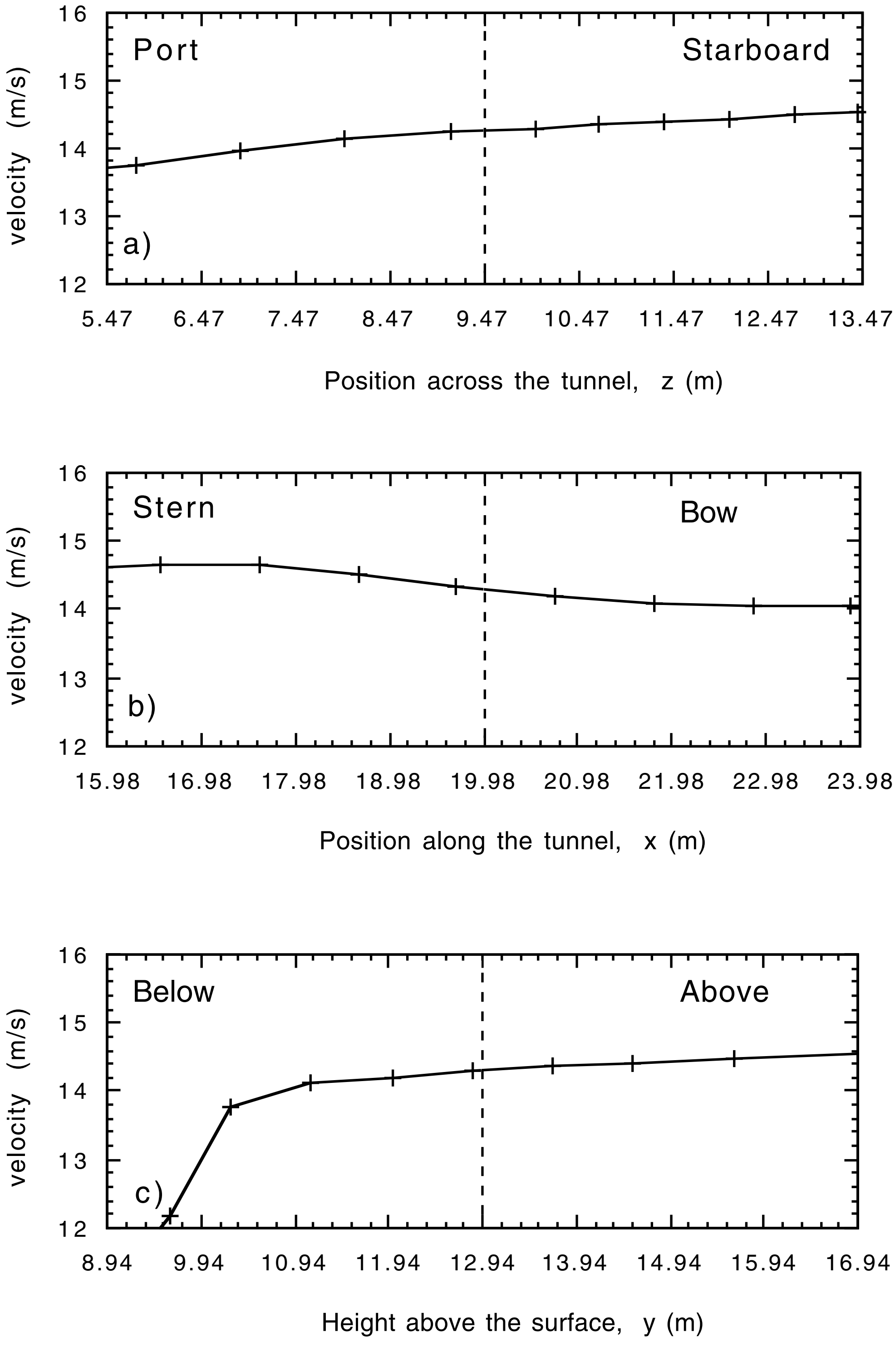


Figure 44 As Figure 41, but for the Vector D anemometer.

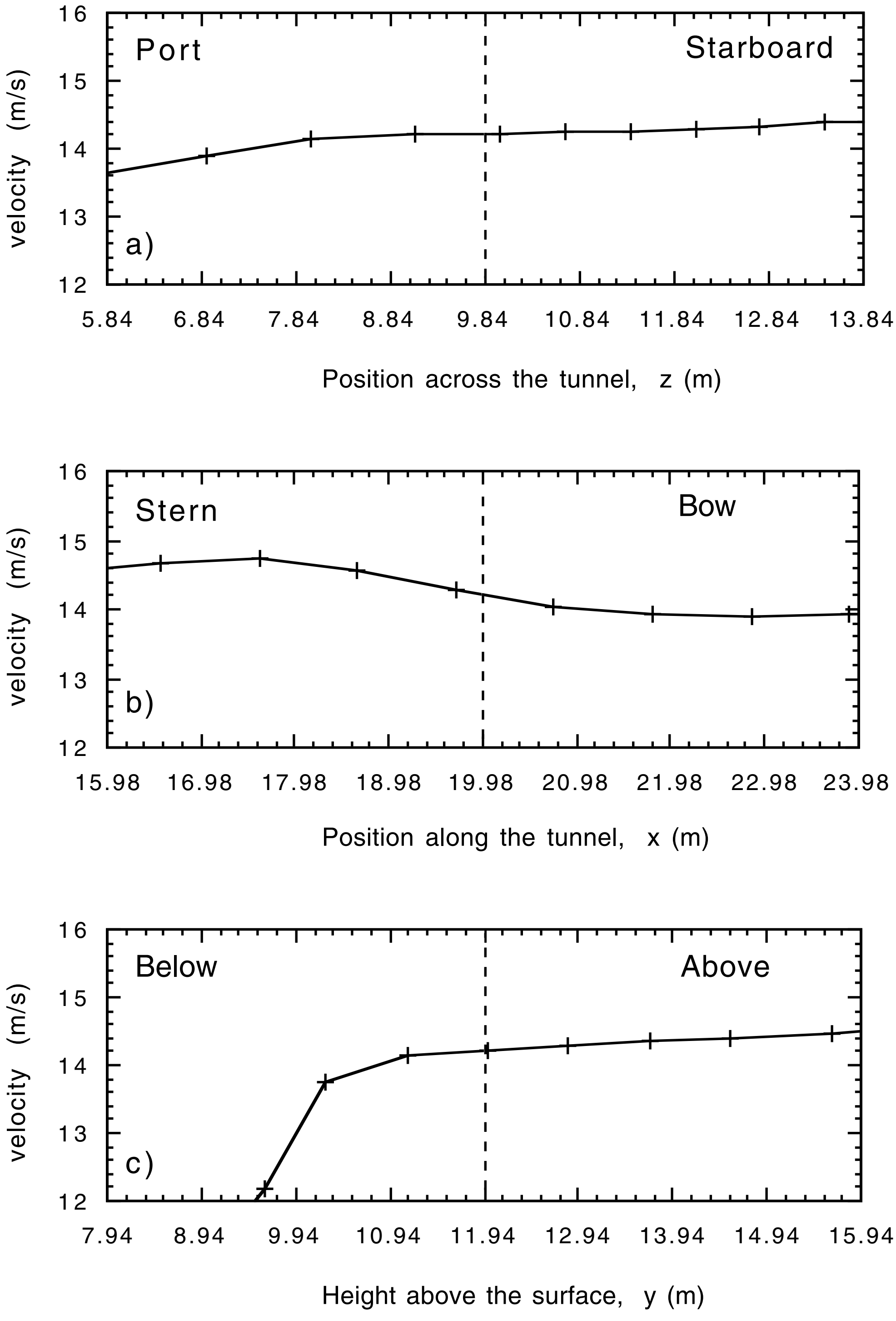
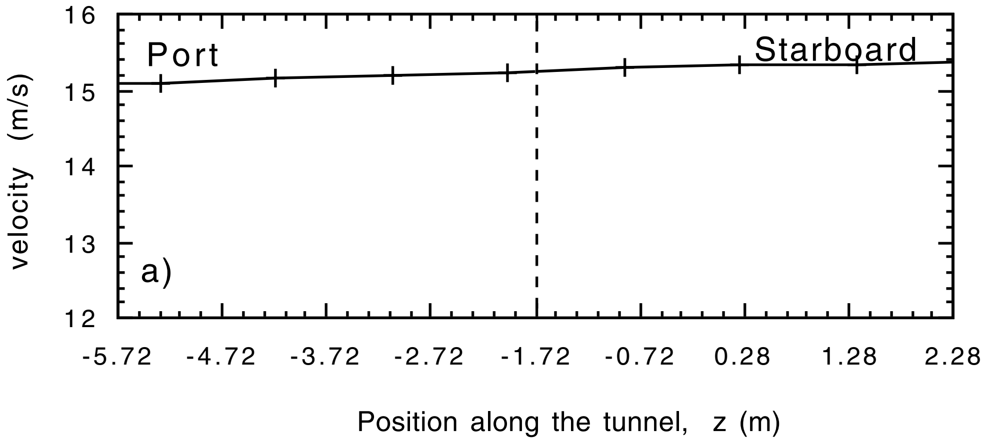
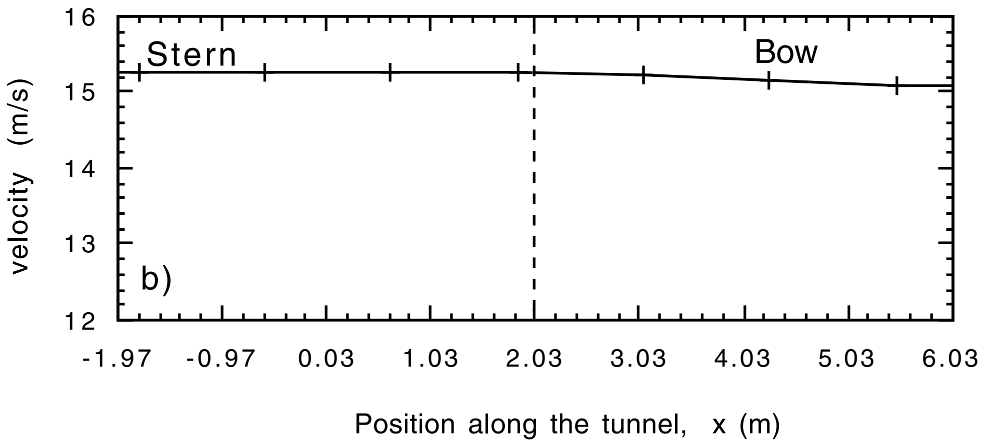


Figure 45 As Figure 41, but for the Vector E (lowest) anemometer.





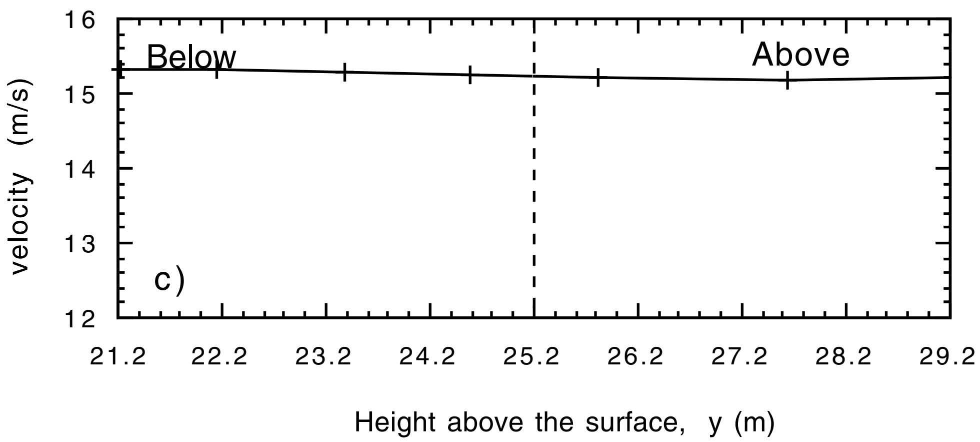


Figure 46 As Figure 38, but for the main mast research sonic anemometer.

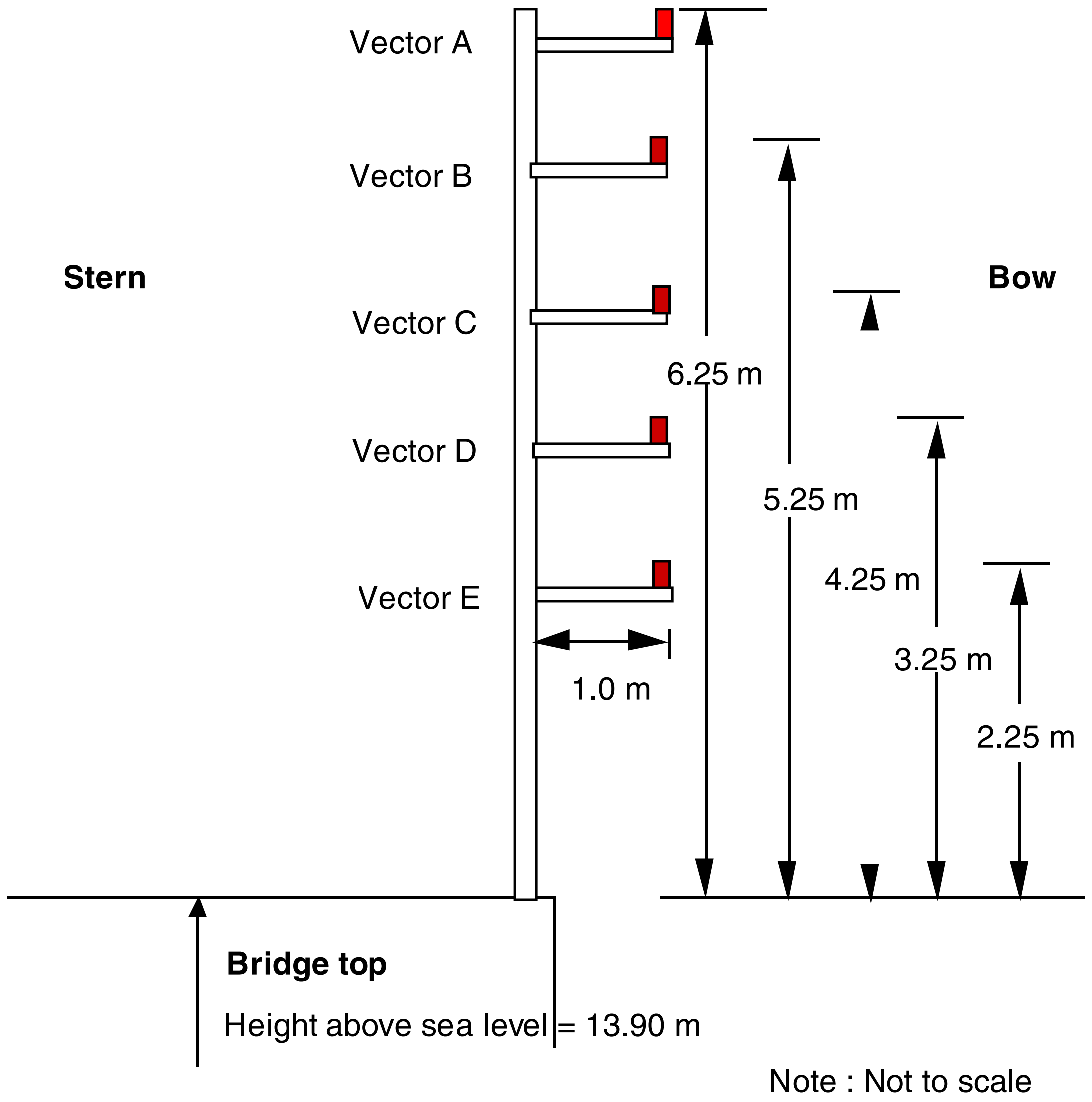


Figure 47 The locations of the Vector anemometers on *R.R.S. Discovery* OMEGA cruise D224.

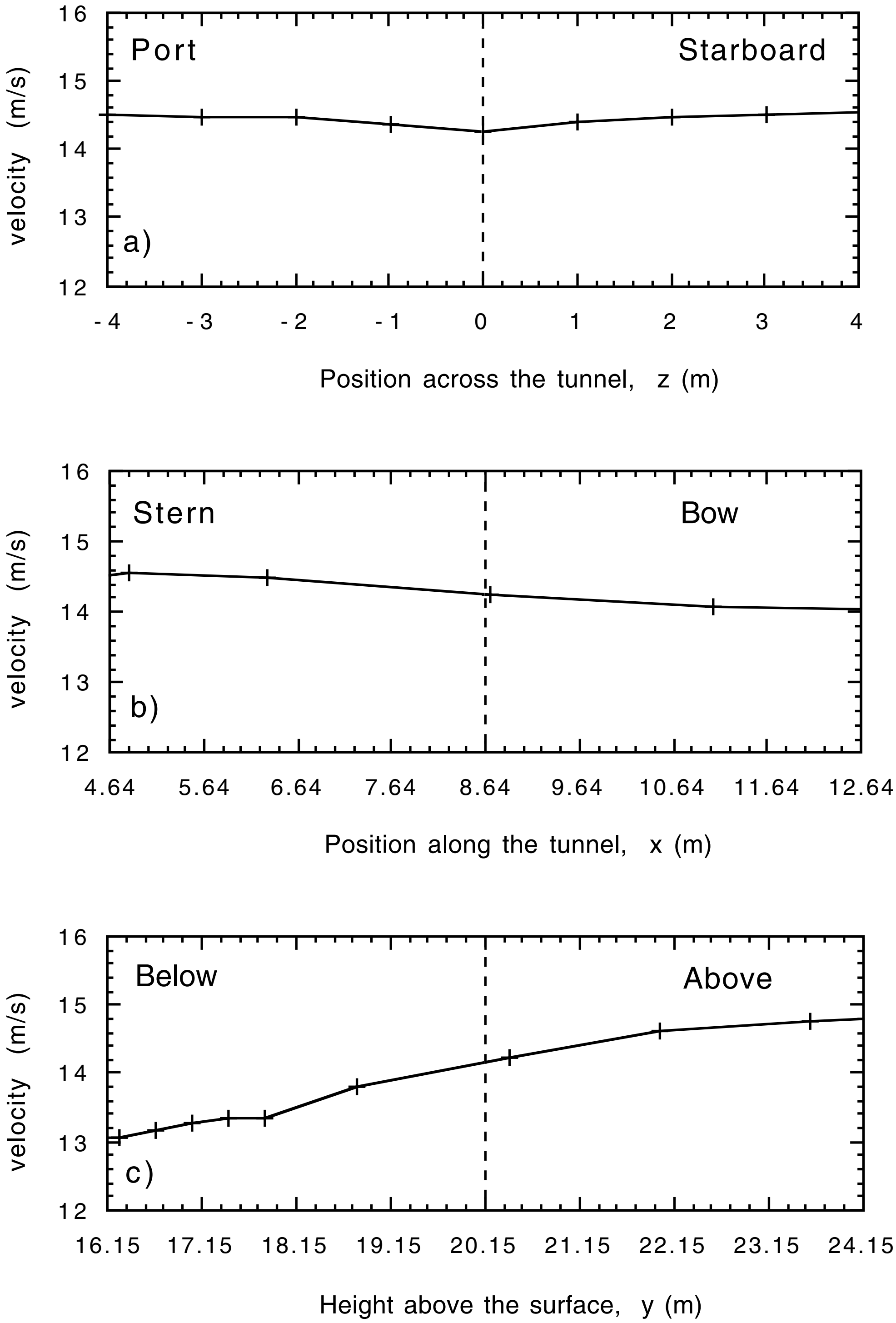


Figure 48 Lines of velocity data through the Vector A (highest) anemometer position (indicated by the dashed line) in all three directions; a) across the tunnel (z), b) along the tunnel (x) and c) vertically (y). Results are from a 0° flow (head to wind) over the bow for cruise D224.

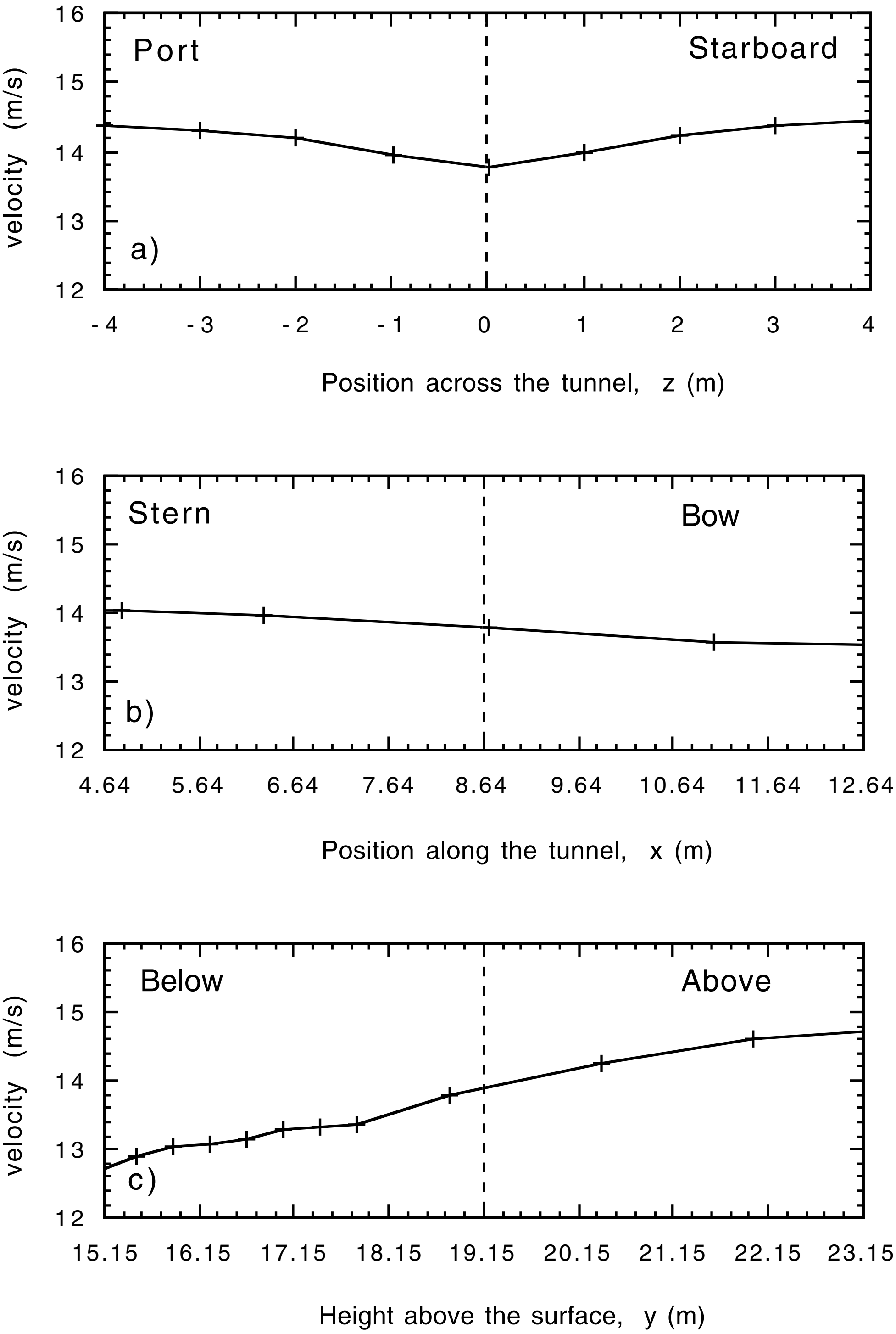


Figure 49 As Figure 48, but for the Vector B anemometer.

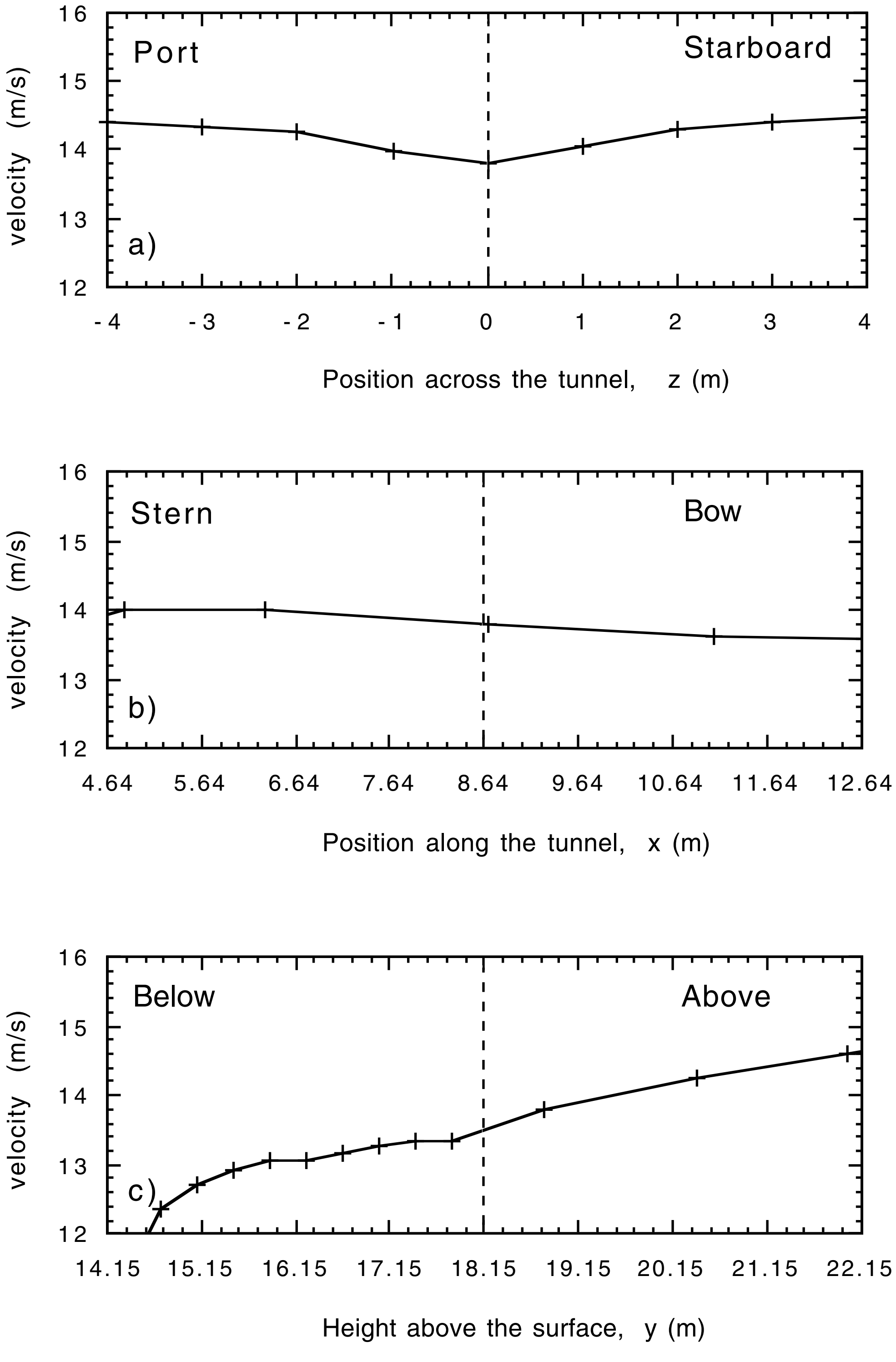


Figure 50 As Figure 48, but for the Vector C anemometer.

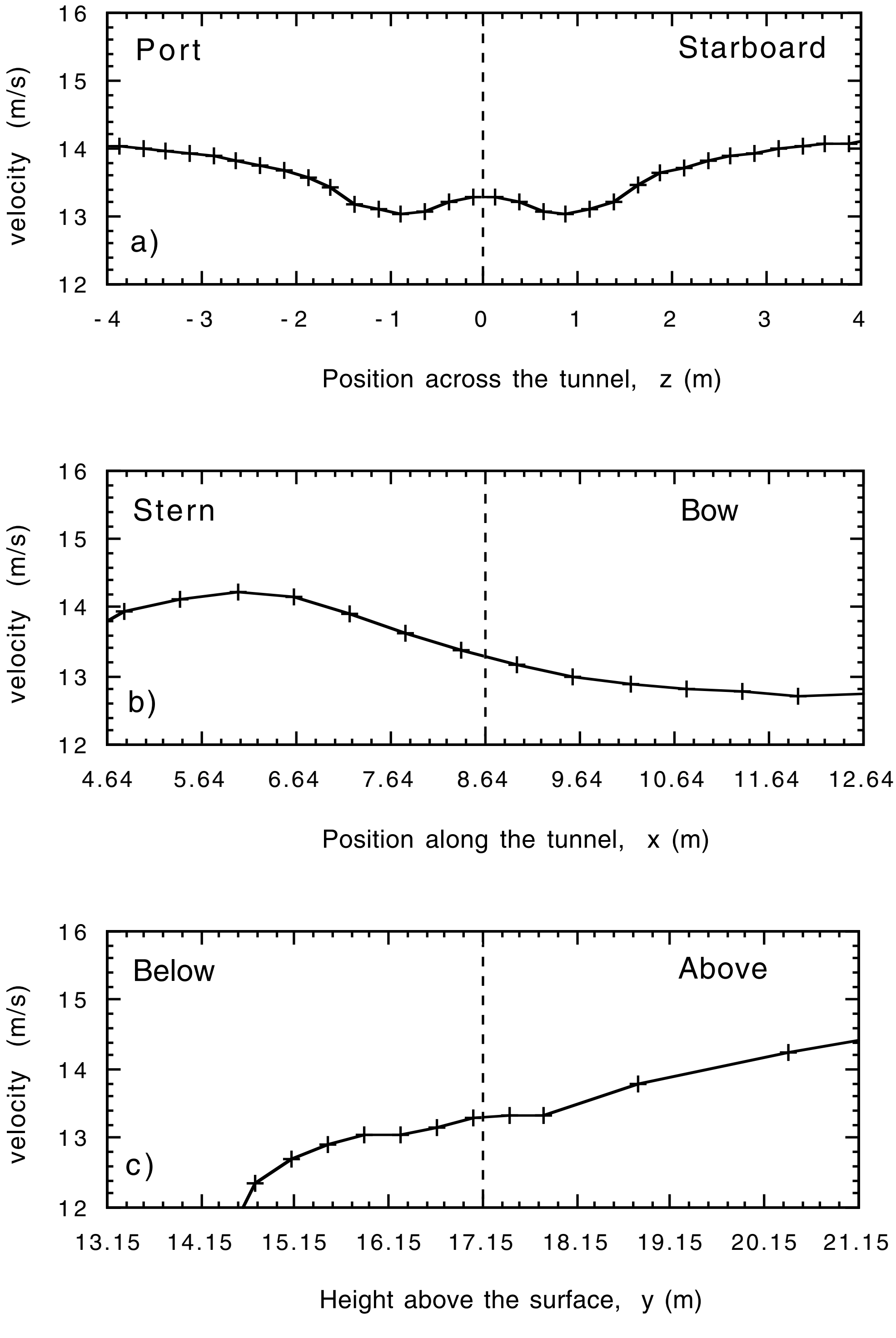


Figure 51 As Figure 48, but for the Vector D anemometer.

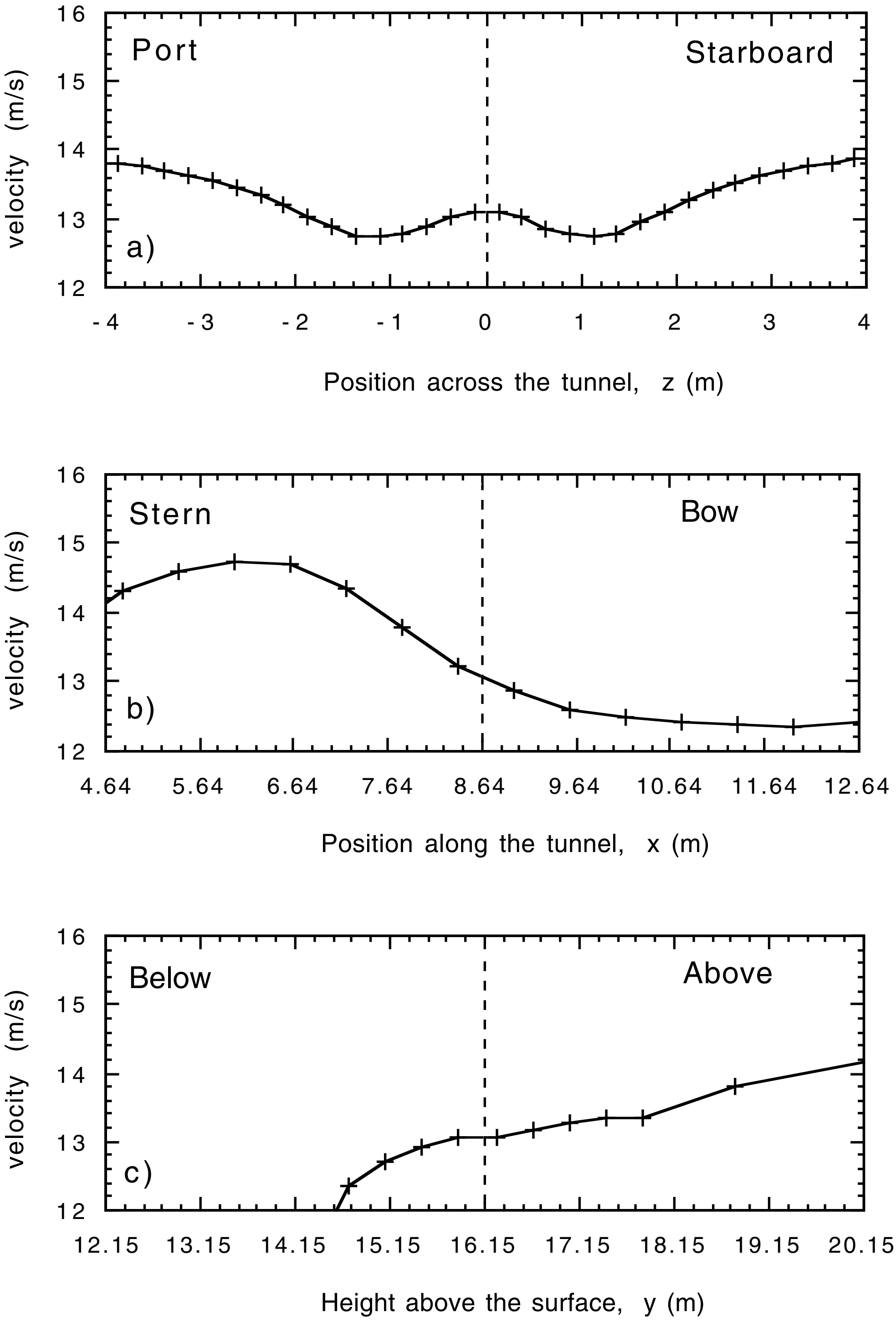


Figure 52 As Figure 48, but for the Vector E (lowest) anemometer.

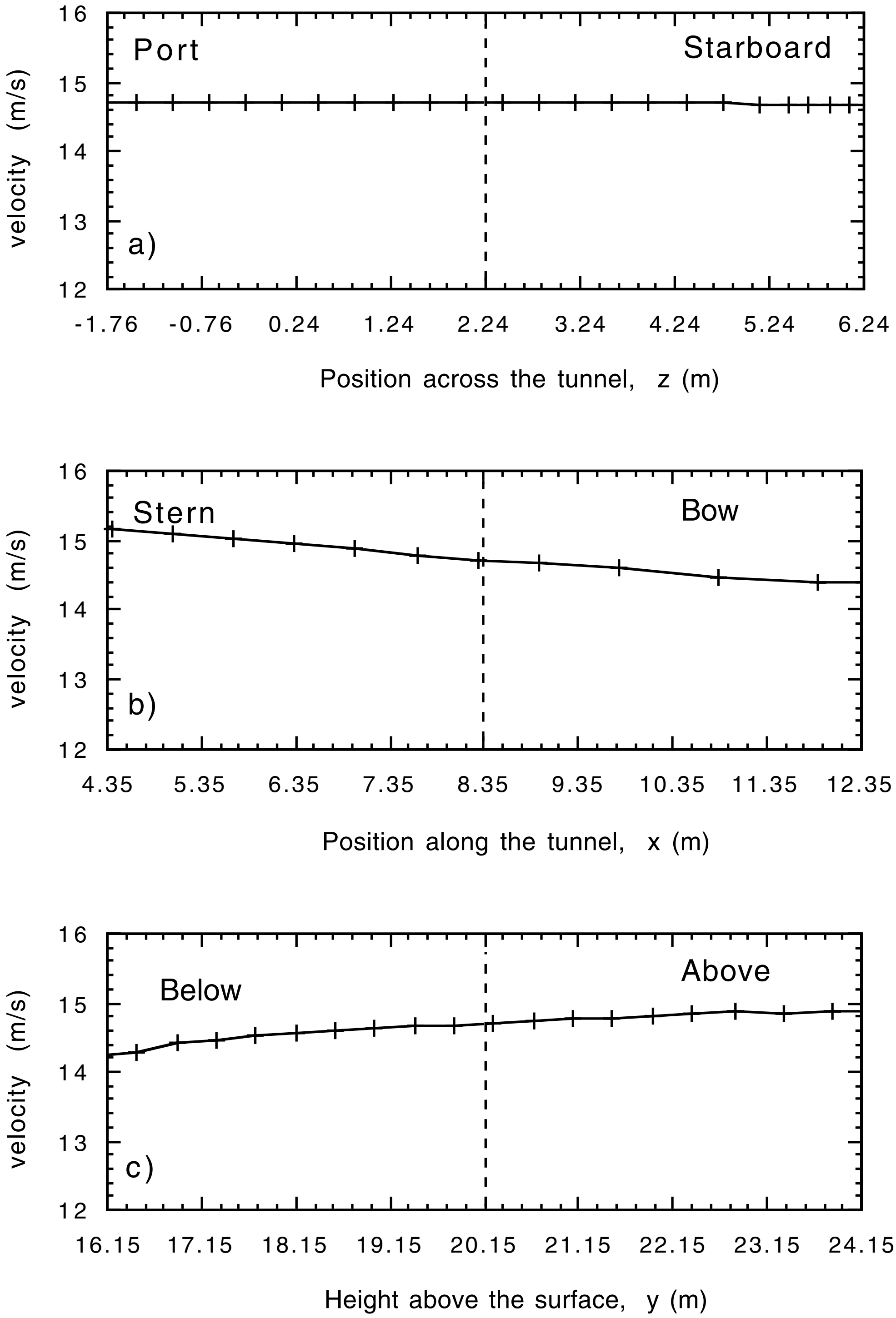


Figure 53 Lines of velocity data through the Vector A (highest) anemometer position (indicated by the dashed line) in all three directions; a) across the tunnel (z), b) along the tunnel (x) and c) vertically (y). Results are from a flow at ±15° over the bow for cruise D224.

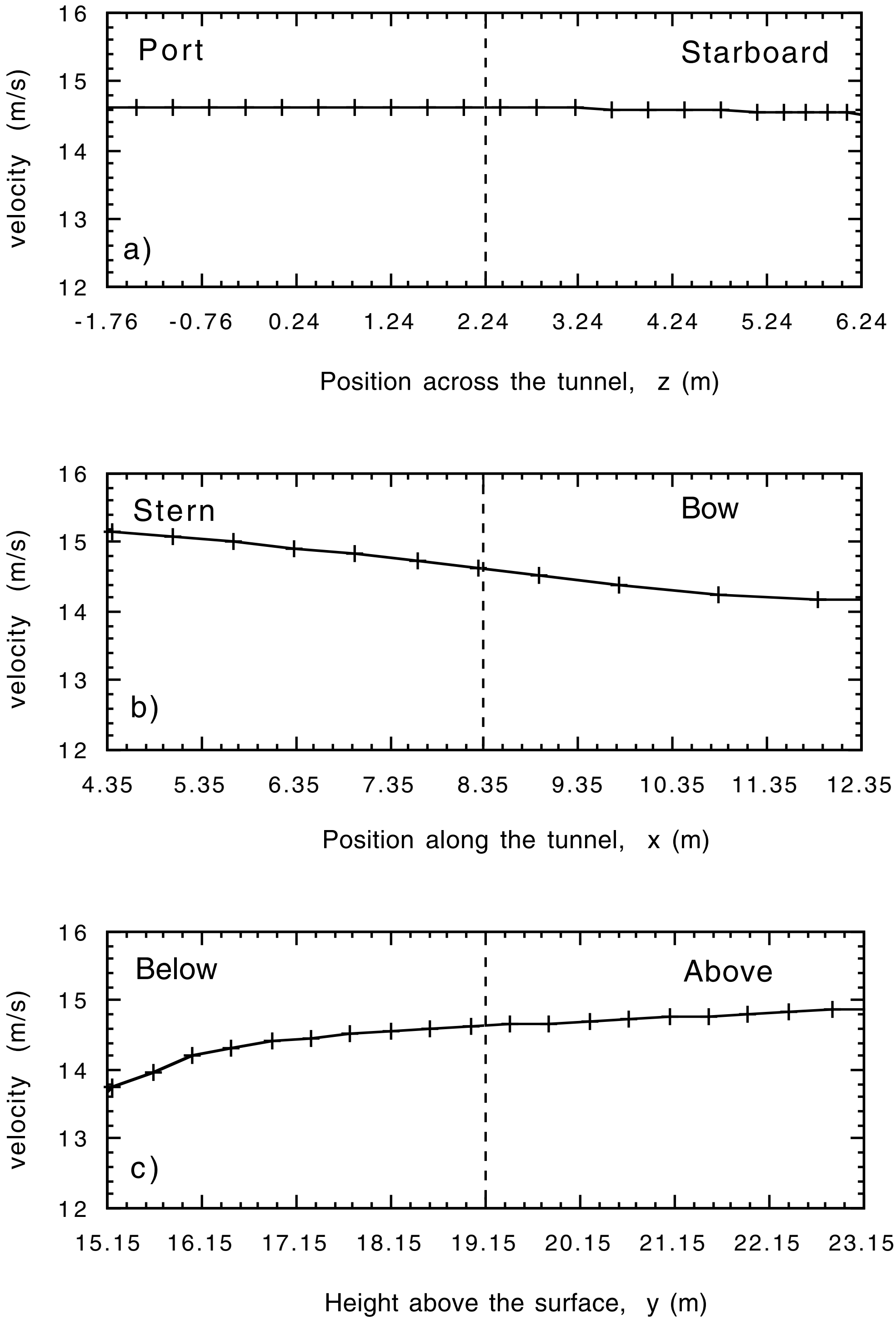


Figure 54 As Figure 53, but for the Vector B anemometer.

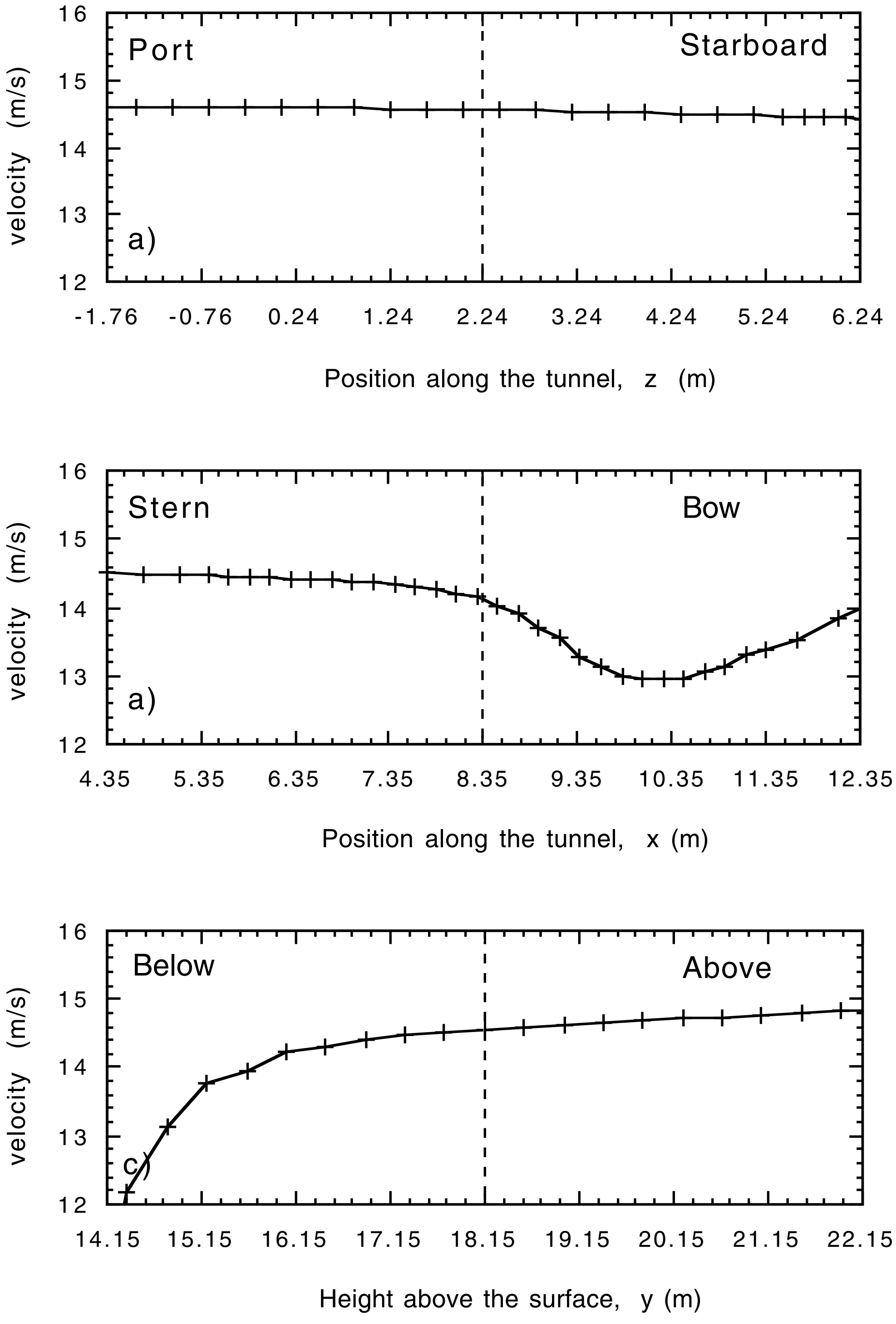


Figure 55 As Figure 53, but for the Vector C anemometer.

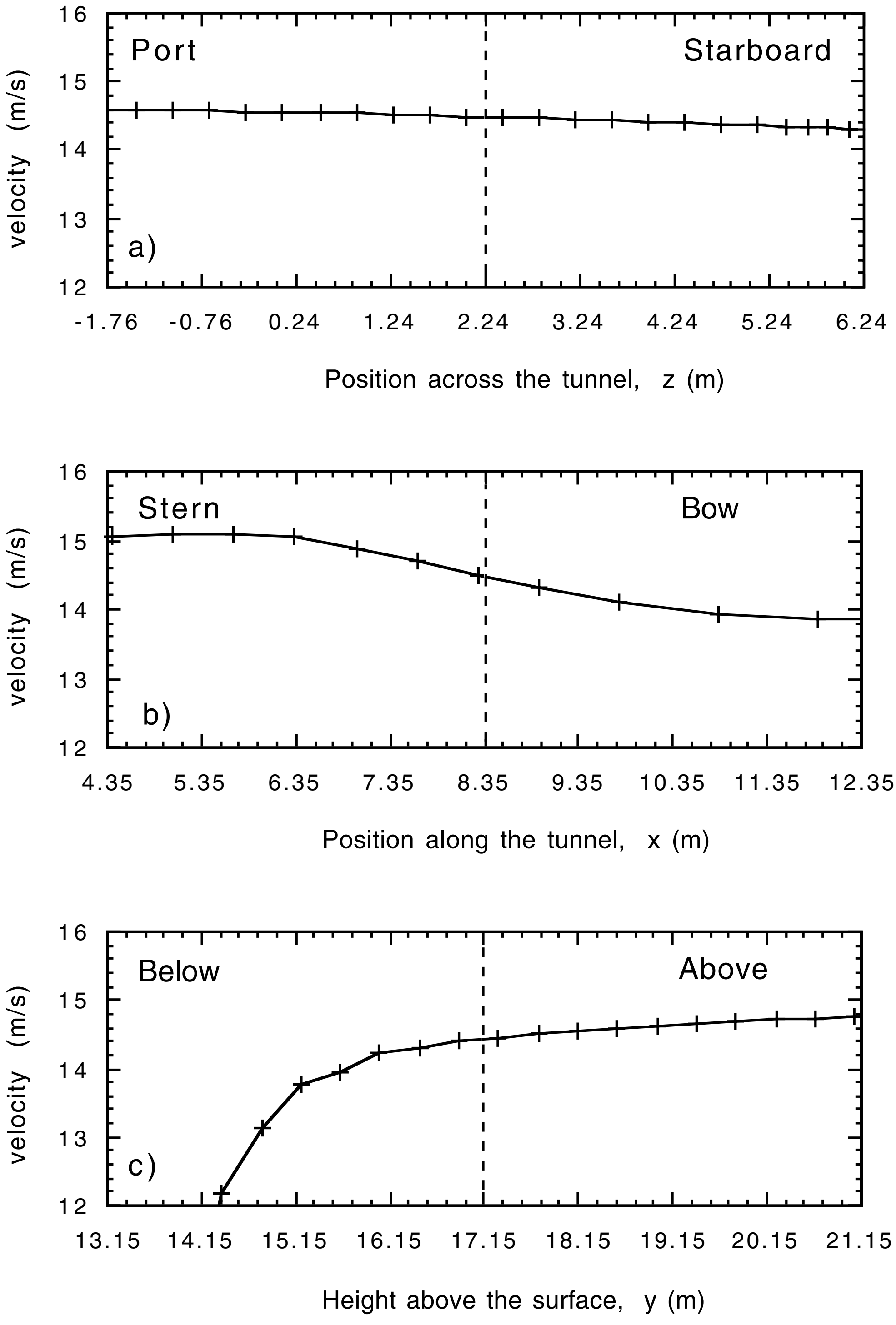


Figure 56 As Figure 53, but for the Vector D anemometer.

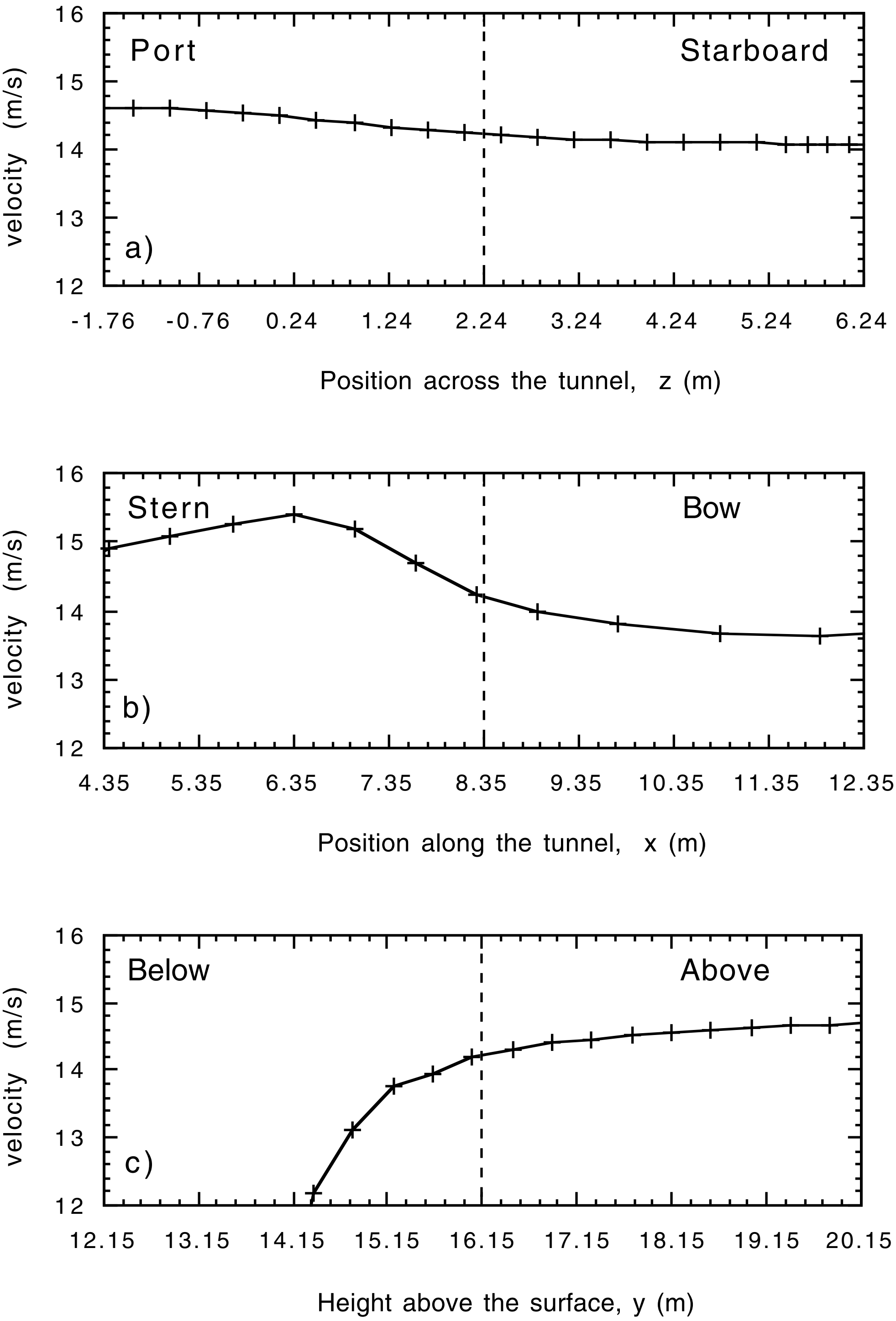
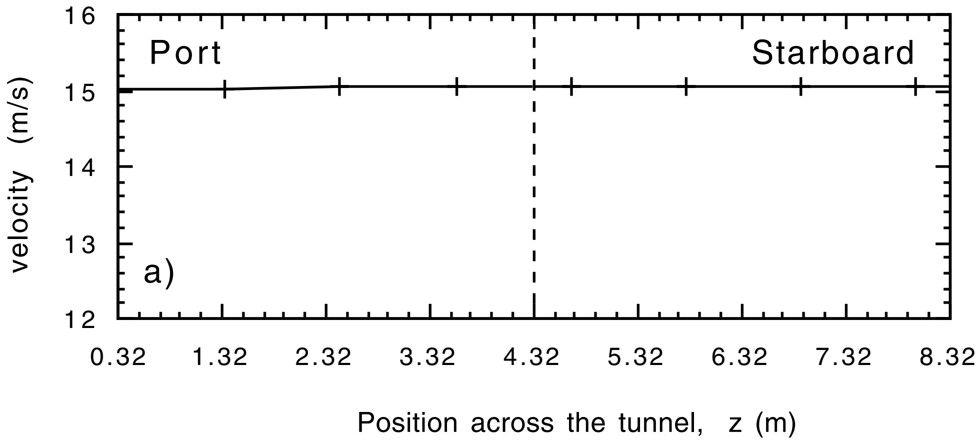
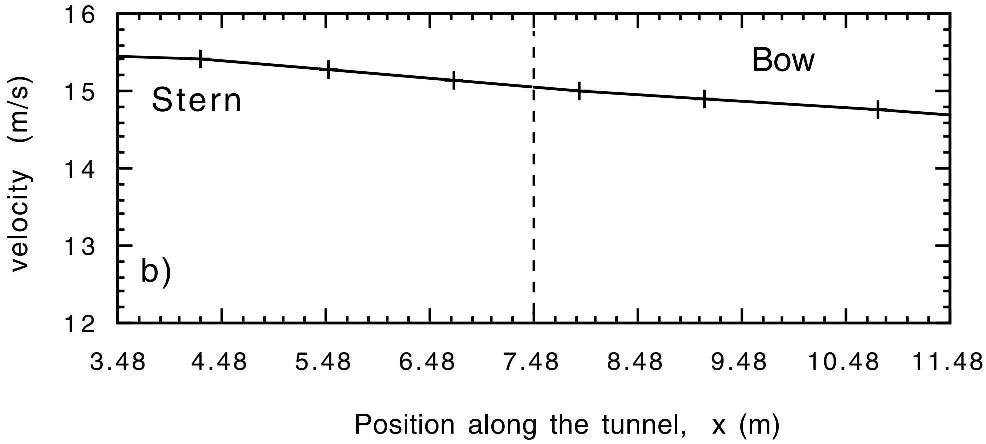


Figure 57 As Figure 53, but for the Vector E (lowest) anemometer.





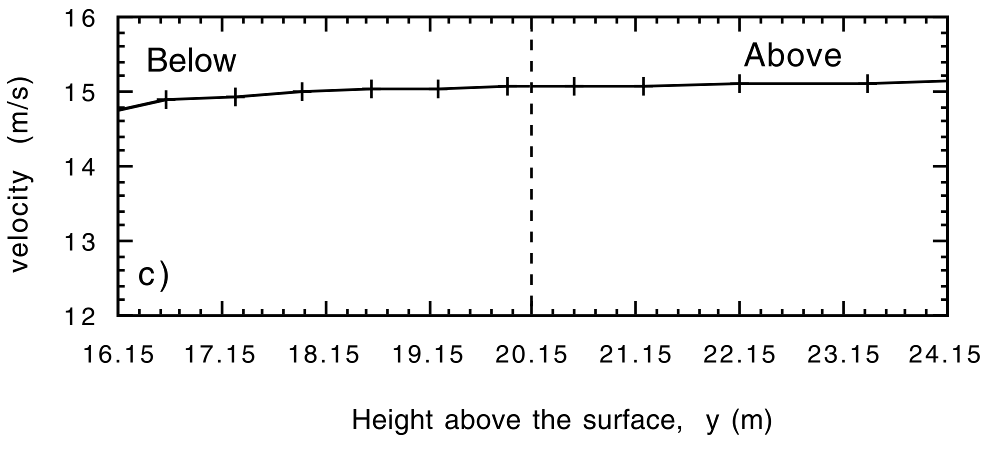


Figure 58 Lines of velocity data through the Vector A (highest) anemometer position (indicated by the dashed line) in all three directions; a) across the tunnel (z), b) along the tunnel (x) and c) vertically (y). Results are from a flow at ±30° over the bow for cruise D224.

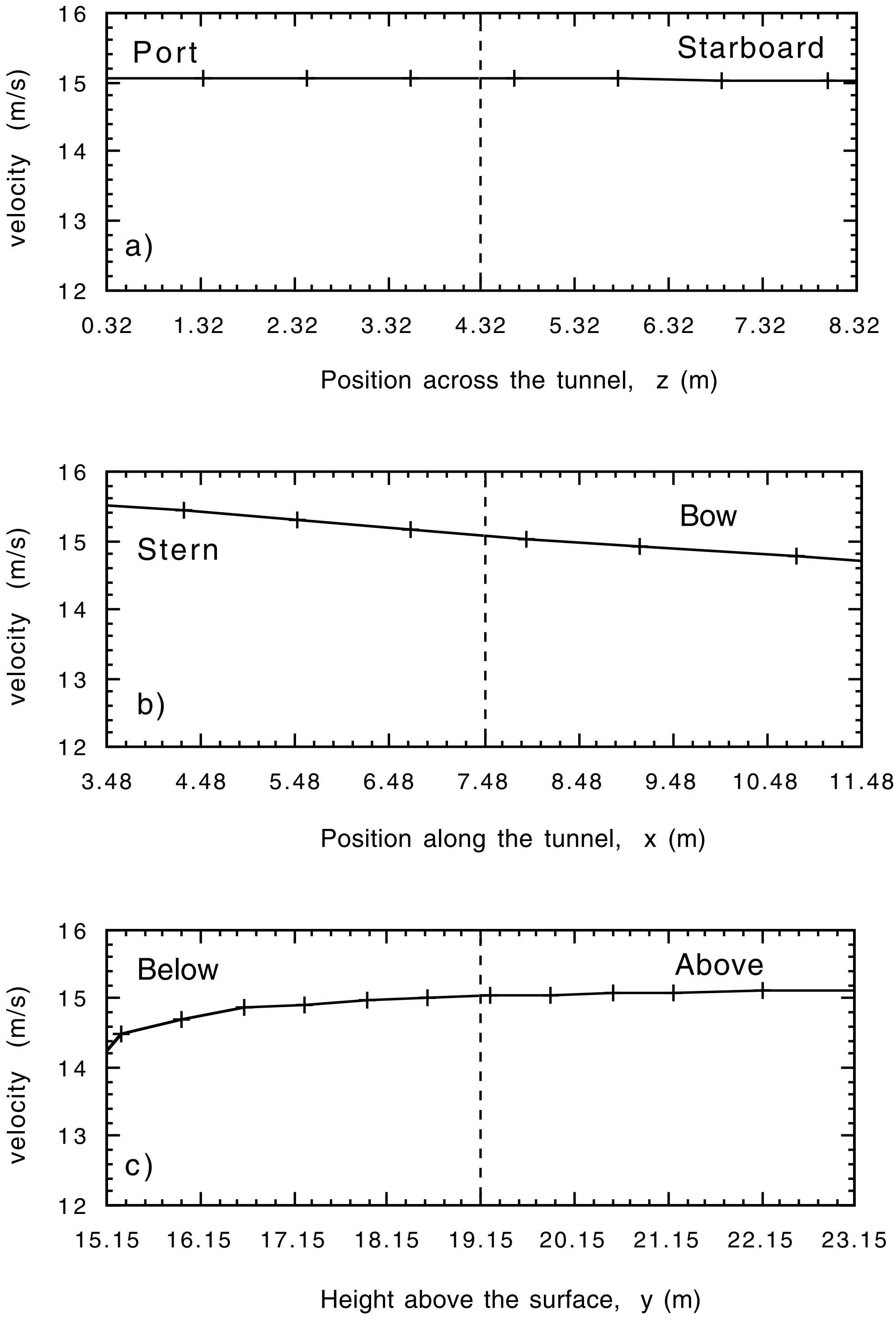


Figure 59 As Figure 58, but for the Vector B anemometer.

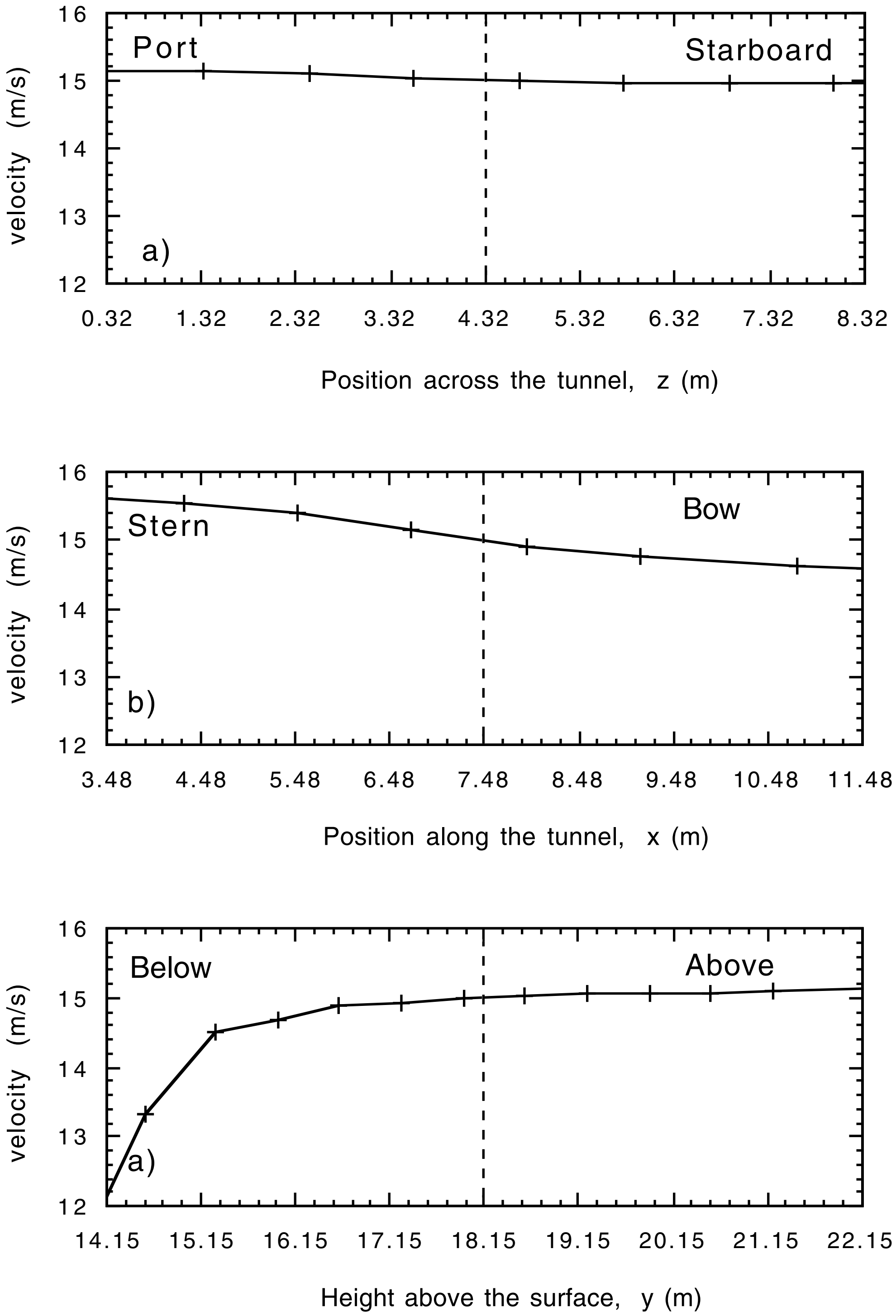


Figure 60 As Figure 58, but for the Vector C anemometer.

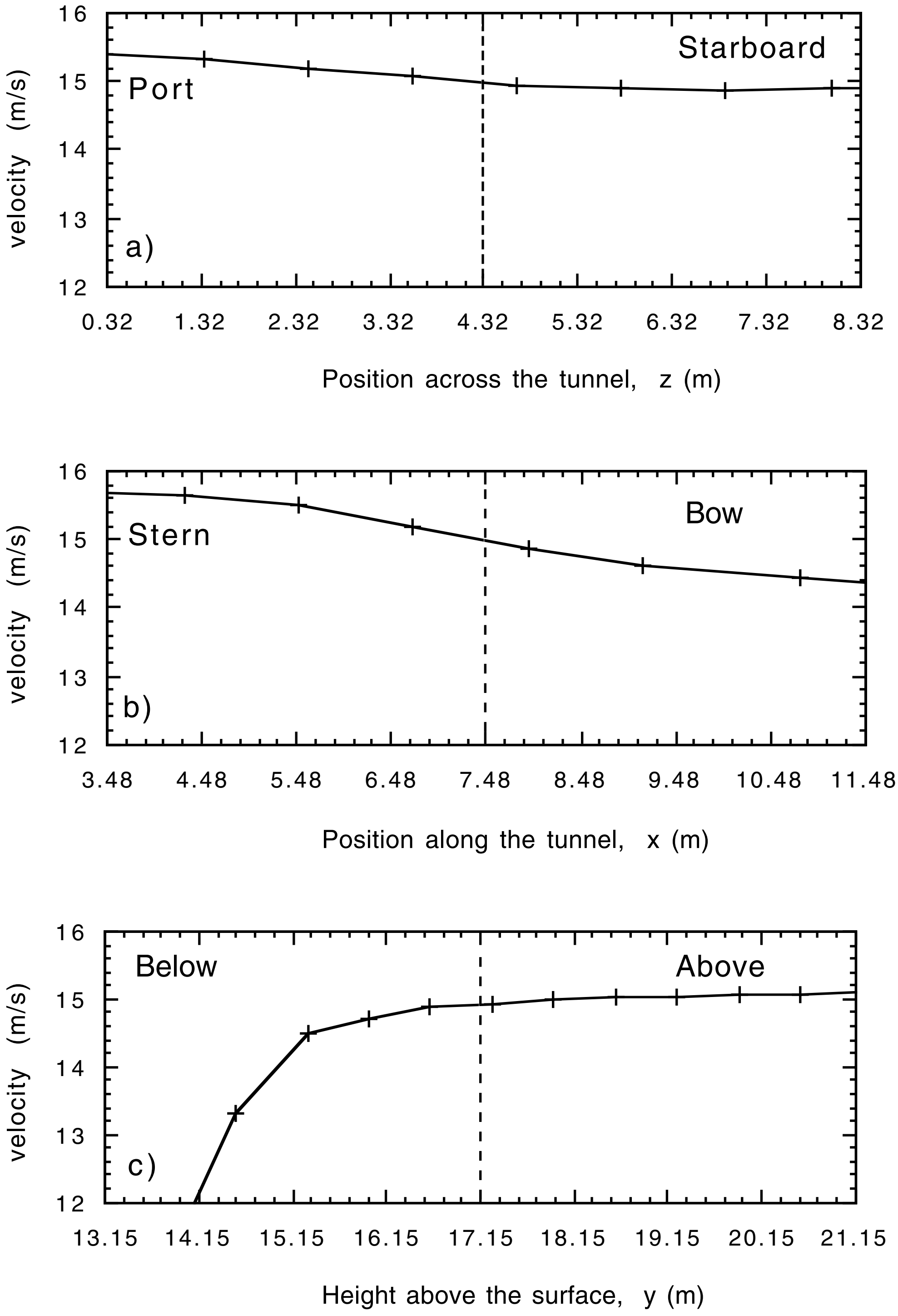


Figure 61 As Figure 58, bit for the Vector D anemometer.

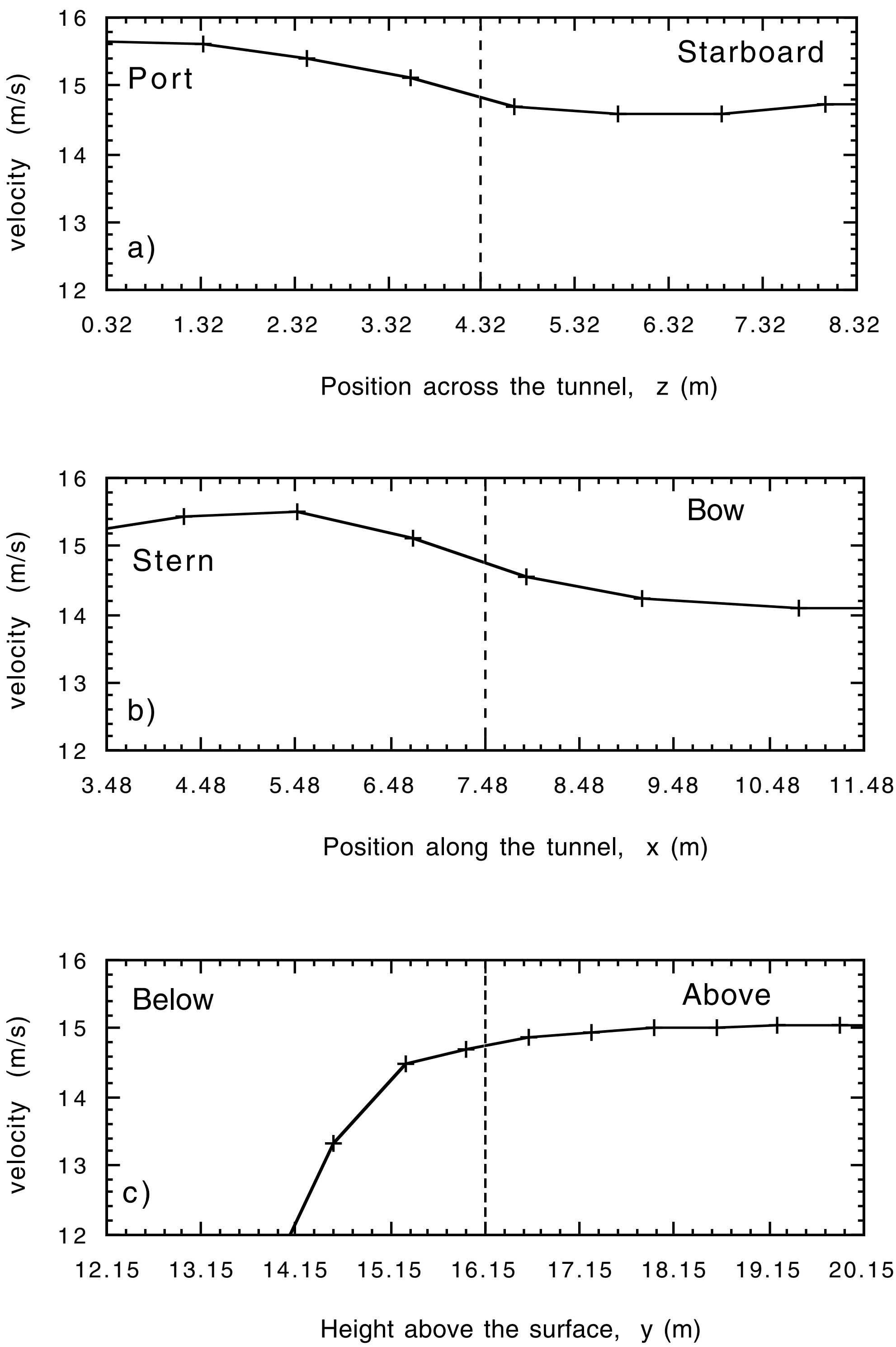


Figure 62 As Figure 58, but for the Vector E anemometer.

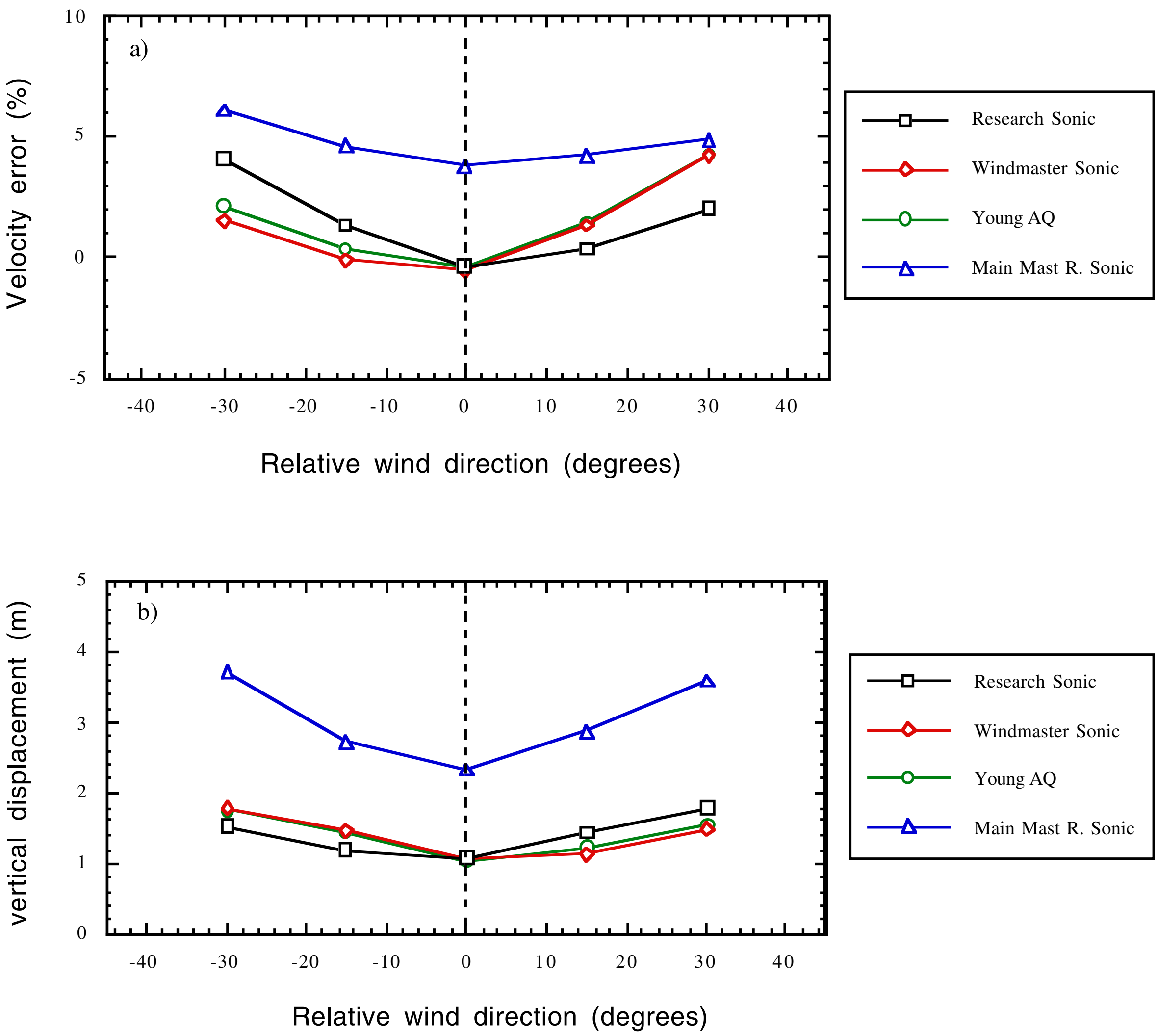


Figure 63 The variation of a) percentage velocity error and b) vertical displacement with relative wind direction for anemometers on D223 and D224.

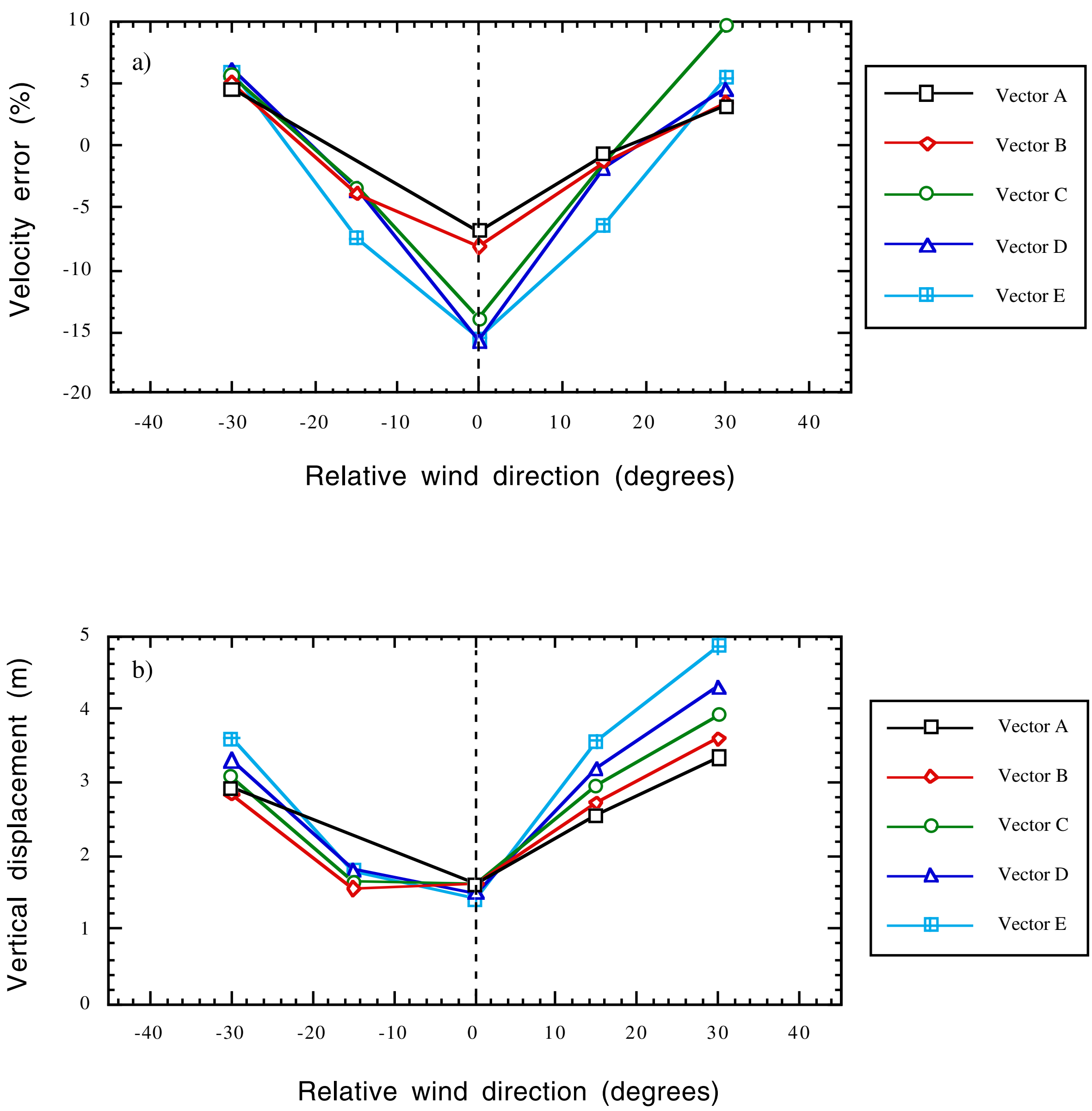


Figure 64 The variation of a) percentage velocity error and b) vertical displacement with relative wind direction for the Vector anemometers on D223.

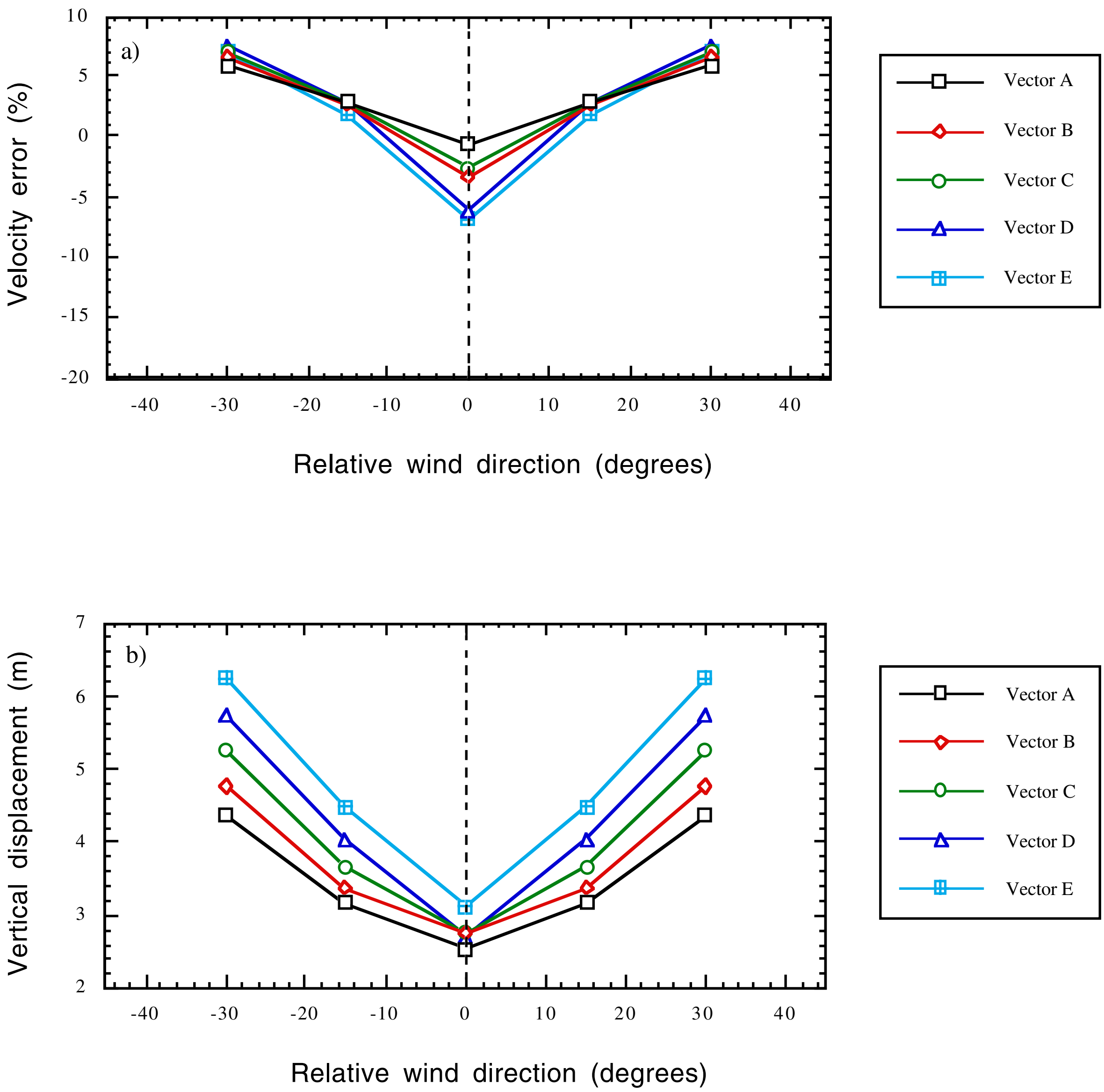


Figure 65 The variation of a) percentage velocity error and b) vertical displacement with relative wind direction for the Vector anemometers on D224.